Multi-hazard Loss Estimation Methodology

Earthquake Model

Hazus®–MH 2.1

Technical Manual

Developed by:
Department of Homeland Security
Federal Emergency Management Agency
Mitigation Division
Washington, D.C.

This manual is available on the FEMA website at www.fema.gov/plan/prevent/hazus.

To order the Hazus software visit www.msc.fema.gov and go to the Product Catalog to place your order

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MESSAGE TO USERS

The Hazus Earthquake Model is designed to produce loss estimates for use by federal, state, regional and local governments in planning for earthquake risk mitigation, emergency preparedness, response and recovery. The methodology deals with nearly all aspects of the built environment, and a wide range of different types of losses. Extensive national databases are embedded within Hazus, containing information such as demographic aspects of the population in a study region, square footage for different occupancies of buildings, and numbers and locations of bridges. Embedded parameters have been included as needed. Using this information, users can carry out general loss estimates for a region. The Hazus methodology and software are flexible enough so that locally developed inventories and other data that more accurately reflect the local environment can be substituted, resulting in increased accuracy.

Uncertainties are inherent in any loss estimation methodology. They arise in part from incomplete scientific knowledge concerning earthquakes and their effects upon buildings and facilities. They also result from the approximations and simplifications that are necessary for comprehensive analyses. Incomplete or inaccurate inventories of the built environment, demographics and economic parameters add to the uncertainty. These factors can result in a range of uncertainty in loss estimates produced by the Hazus Earthquake Model, possibly *at best* a factor of two or more.

The methodology has been tested against the judgment of experts and, to the extent possible, against records from several past earthquakes. However, limited and incomplete data about actual earthquake damage precludes complete calibration of the methodology. Nevertheless, when used with embedded inventories and parameters, the Hazus Earthquake Model has provided a credible estimate of such aggregated losses as the total cost of damage and numbers of casualties. The Earthquake Model has done less well in estimating more detailed results - such as the number of buildings or bridges experiencing different degrees of damage. Such results depend heavily upon accurate inventories. The Earthquake Model assumes the same soil condition for all locations, and this has proved satisfactory for estimating regional losses. Of course, the geographic distribution of damage may be influenced markedly by local soil conditions. In the few instances where the Earthquake Model has been partially tested using actual inventories of structures plus correct soils maps, it has performed reasonably well.

Users should be aware of the following specific limitations:

- While the Hazus Earthquake Model can be used to estimate losses for an individual building, the results must be considered as average for a group of similar buildings. It is frequently noted that nominally similar buildings have experienced vastly different damage and losses during an earthquake.

- When using embedded inventories, accuracy of losses associated with lifelines may be less than for losses from the general building stock. The embedded databases and assumptions used to characterize the lifeline systems in a study region are necessarily incomplete and oversimplified.
- Based on several initial studies, the losses from small magnitude earthquakes (less than M6.0) centered within an extensive urban region appear to be overestimated.
- Because of approximations in modeling of faults in California, there may be discrepancies in motions predicted within small areas immediately adjacent to faults.
- There is considerable uncertainty related to the characteristics of ground motion in the Eastern U.S. The embedded attenuation relations in the Earthquake Model, which are those commonly recommended for design, tend to be conservative. Hence use of these relations may lead to overestimation of losses in this region, both for scenario events and when using probabilistic ground motion.

Hazus should still be regarded as a work in progress. Additional damage and loss data from actual earthquakes and further experience in using the software will contribute to improvements in future releases. To assist us in further improving Hazus, users are invited to submit comments on methodological and software issues by letter, fax or e-mail to:

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WHAT'S NEW IN Hazus - EARTHQUAKE MODEL

Please refer to **Getting Started.pdf** document for a list of the new features in Hazus-MH 2.1.

The document has also details about the installation of the software, its limitations and capabilities, and information on how to obtain technical support.

Chapter 1
Introduction to the FEMA Loss Estimation Methodology

1.1 Background

The Technical Manual describes the methods for performing earthquake loss estimation. It is based on a multi-year project to develop a nationally applicable methodology for estimating potential earthquake losses on a regional basis. The project has being conducted for the National Institute of Building Science (NIBS) under a cooperative agreement with the Federal Emergency Management Agency (FEMA).

The primary purpose of the project is to develop guidelines and procedures for making earthquake loss estimates at a regional scale. These loss estimates would be used primarily by local, state and regional officials to plan and stimulate efforts to reduce risks from earthquakes and to prepare for emergency response and recovery. A secondary purpose of the project is to provide a basis for assessing nationwide risk of earthquake losses.

The methodology development and software implementation has been performed by a team of earthquake loss experts composed of earth scientists, engineers, architects, economists, emergency planners, social scientists and software developers. The Earthquake Committee has provided technical direction and review of work with guidance from the Project Oversight Committee (POC), a group representing user interests in the earthquake engineering community.

1.2 Technical Manual Scope

The scope of the *Technical Manual* includes documentation of all methods and data that are used by the methodology. Loss estimation methods and data are obtained from referenced sources tailored to fit the framework of the methodology, or from new methods and data developed when existing methods and data were lacking or were not current with the state of the art.

The *Technical Manual* is a comprehensive, highly technical collection of methods and data covering a broad range of topics and disciplines, including earth science, seismic/structural engineering, social science and economics. The *Technical Manual* is written for readers who are expected to have some degree of expertise in the technical topic of interest, and may be inappropriate for readers who do not have this background.

As described in Chapter 2, a separate *User Manual* describes the earthquake loss estimation methodology in non-technical terms and provides guidance to users in the application of the methodology. The methodology software is implemented using Geographical Information System (GIS) software as described in the *Technical Manual*.

1.3 Technical Manual Organization

The *Technical Manual* contains sixteen chapters. Chapter 2 describes the overall framework of the methodology and provides background on the approach developed used to meet the project's objectives. Chapter 3 discusses inventory data, including classification schemes of different systems, attributes required to perform damage and loss estimation, and the data supplied with the methodology. Sources and methods of collection of inventory data are not covered in Chapter 3, but may be found in the *User Manual*.

Chapters 4 through 16 cover, respectively, each of thirteen major components or subcomponents (modules) of the methodology. Each of the major components and subcomponents are described in Chapter 2. A flowchart is provided in Chapter 2 as a "road map" of the relationships between modules of the methodology. This flowchart is repeated at the beginning of each chapter with the module of interest high-lighted to show input from and output to other modules of the methodology.

Chapter 2
Overall Approach and Framework of Methodology

This chapter describes the overall approach used by the developers to meet the objectives of the project, the components and subcomponents of earthquake loss estimation and their relationship within the framework of methodology.

2.1 Vision Statement

The overall approach for the project is based on the following "vision" of the earthquake loss estimation methodology.

> *The earthquake loss estimation methodology will provide local, state and regional officials with the tools necessary to plan and stimulate efforts to reduce risk from earthquakes and to prepare for emergency response and recovery from an earthquake. The methodology will also provide the basis for assessment of nationwide risks of earthquake loss.*
>
> *The methodology can be used by a variety of users with needs ranging from simplified estimates that require minimal input to refined calculations of earthquake loss. The methodology may be implemented using either geographical information system (GIS) technology provided in a software package or by application of the theory documented in a Technical Manual. An easily understood User Manual will guide implementation of the methodology by either technical or non-technical users.*

The vision of earthquake loss estimation requires a methodology that is both flexible, accommodating the needs of a variety of different users and applications, and able to provide the uniformity of a standardized approach. The framework of the methodology includes each of the components shown in Figure 2-1: Potential Earth Science Hazard (PESH), Inventory, Direct Physical Damage, Induced Physical Damage, Direct Economic/Social Loss and Indirect Economic Loss. As indicated by arrows in the figure, modules are interdependent with output of some modules acting as input to others. In general, each of the components will be required for loss estimation. However, the degree of sophistication and associated cost will vary greatly by user and application. It is therefore necessary and appropriate that components have multiple levels (multiple modules) of detail or precision when required to accommodate user needs.

Framing the earthquake loss estimation methodology as a collection of modules permits adding new modules (or improving models/data of existing modules) without reworking the entire methodology. Improvements may be made to adapt modules to local or regional needs or to incorporate new models and data. The modular nature of the methodology permits a logical evolution of the methodology as research progresses and the state-of-the-art advances.

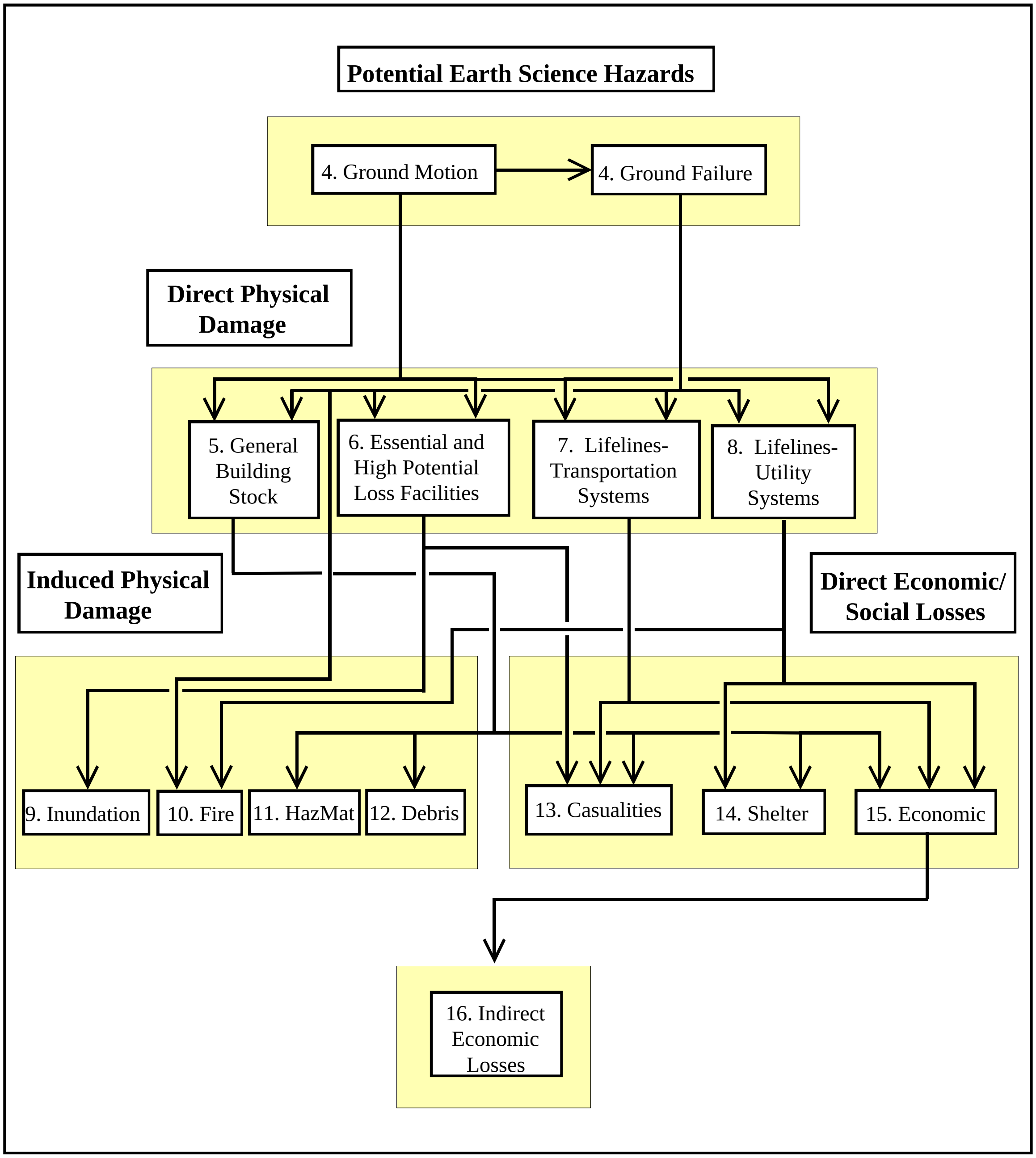

Figure 2.1 Flowchart of the Earthquake Loss Estimation Methodology.

Most users will implement the methodology using the GIS-based software application provided by NIBS. After initial inventory entry, the program will run efficiently on desktop computer. The GIS technology provides a powerful tool for displaying outputs and permits users to "see" the effects of different earthquake scenarios and assumptions. A *User Manual* will guide users in program manipulation, input of new data, and changes to existing data.

Certain users may not wish to use the software application, or may want to augment the results with supplementary calculations. In such cases, users can refer to the *Technical Manual* for a complete description of models and data of each module. The *Technical Manual* is useful to technical experts, such as those engineers and scientists that have conducted previous earthquake loss studies, but might be inappropriate for non-technical users.

Both technical and non-technical users are guided in the application of the methodology by the *User Manual*, which addresses important implementation issues, such as:

(1) Selection of scenario earthquakes and PESH inputs
(2) Selection of appropriate methods (modules) to meet different user needs
(3) Collection of required inventory data, i.e., how to obtain necessary information
(4) Costs associated with inventory collection and methodology implementation
(5) Presentation of results including appropriate terminology, etc.
(6) Interpretation of results including consideration of model/data uncertainty.

The three project deliverables are shown in Figure 2.2.

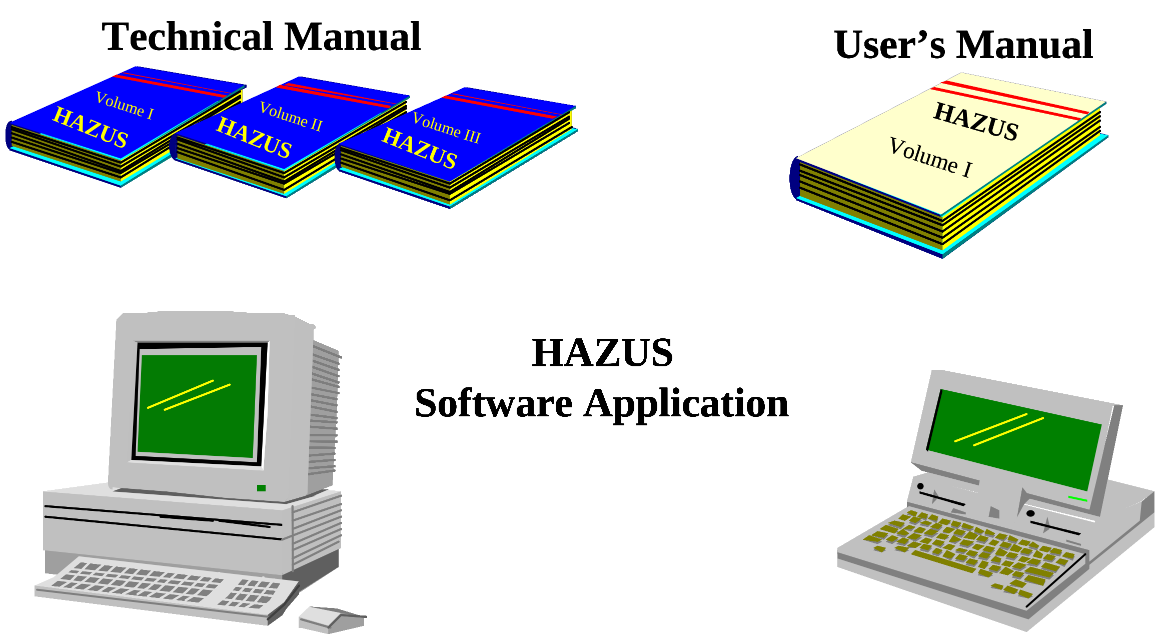

Figure 2.2 Project Deliverables.

2.2 Project Objectives

The development of an earthquake loss estimation methodology has been defined by the eight General Objectives outlined in the NIBS/FEMA "Task Plan for Tasks 2 and 5," October 18, 1993. The following sections summarize the approach taken to meet each objective.

Accommodation of User Needs

The methodology utilizes a modular approach with different modules addressing different user needs. This approach avoids the need to decide on who is the designated user. The needs of most, if not all, users are accommodated by the flexibility of a modular approach.

The GIS technology permits easy implementation by users on desktop computers. The visual display and interactive nature of a GIS application provides an immediate basis for exchange of information and dialog with end-users of the results. The *User Manual* provides appropriate terminology and definitions, and user-oriented descriptions of the loss estimation process.

State-of-the-Art

The methodology incorporates available state-of-the-art models in the earthquake loss estimation methodology. For example, ground shaking hazard and related damage functions are described in terms of spectral response rather than MMI. Modules include damage loss estimators not previously found in most studies, such as induced damage due to fire following earthquake and indirect economic loss. A nationally applicable scheme is developed for classifying buildings, structures and facilities.

Balance

The methodology permits users to select methods (modules) that produce varying degrees of precision. The *User Manual* provides guidance to users regarding the selection of modules that are appropriate for their needs and which have a proper balance between different components of earthquake loss estimation.

Flexibility in Earthquake Demand

The methodology incorporates both deterministic (scenario earthquake) and probabilistic descriptions of spectral response. Alternatively, the proposed methodology accepts user-supplied maps of earthquake demand. The software application is structured to also accept externally supplied maps of earthquake ground shaking.

"Uncertainty" in earthquake demand due to spatial variability of ground motion is addressed implicitly by the variability of damage probability matrices (DPM's) or fragility curves. Uncertainty in earthquake demand due to temporal variability (i.e., earthquake recurrence rate) or uncertainty in the magnitude of earthquake selected for scenario event may be readily evaluated by the users.

Once the data is input into the software application, any number of scenario events can be evaluated. The *User Manual* provides guidance for the consideration of uncertainty, including that associated with earthquake demand.

Uses of Methodology Data

The *User Manual* provides recommendations for collecting inventory data that will permit use of the data for non-earthquake purposes. Inventory information will come from databases supplied with the methodology and/or collected in databases compatible with the software. Such data will be available to users for other applications.

Accommodation of Different Levels of Funding

The methodology includes modules that permit different levels of inventory collection and associated levels of funding. For example, the methodology permits simplified (Default Data Analysis) estimates of damage and loss, using primarily default data supplied with the software application. These estimates of damage/loss do not require extensive inventory collection and can be performed on a modest budget. More precise damage/loss (User-Supplied Data Analysis) estimates require more extensive inventory information at additional cost to the user. The *User Manual* provides guidance to users regarding trade-offs in cost and accuracy of results.

Standardization

The methodology includes standard methods for:

(1) Inventory data collection based on census tract areas
(2) Using database maps of soil type, ground motion, ground failure, etc.
(3) Classifying occupancy of buildings and facilities
(4) Classifying building structure type
(5) Describing damage states
(6) Developing building damage functions
(7) Grouping, ranking and analyzing lifelines
(7) Using technical terminology
(8) Providing output.

Non-Proprietary

The methodology includes only non-proprietary loss estimation methods. The software application is non-proprietary to the extent permitted by the GIS-software suppliers.

2.3 Description of Loss Estimation Methodology

The earthquake loss estimation methodology is an improvement over existing regional loss estimation methodologies, since it more completely addresses regional impacts of earthquakes that have been omitted or at best discussed in a qualitative manner in previous studies. Examples of these impacts are service outages for lifelines, estimates of fire ignitions and fire spread, potential for a serious hazardous materials release incident, and indirect economic effects. In addition, strength of this methodology is the ability to readily display inputs and outputs on GIS-based maps that can be overlaid. By overlaying maps the user is able to experiment with different scenarios and ask "what if" questions.

As discussed in Section 2.1, the methodology is modular, with different modules interacting in the calculation of different losses. Figure 2.1 shows each of the modules and the flow of information among them. It can be seen that, because of the complexity of earthquake damage and loss estimation, the model is complex. One advantage of the modularity of the methodology is that it enables users to limit their studies to selected losses. For example, a user may wish to ignore induced physical damage when computing direct economic and social losses. This would eliminate the lower left portion of the flow diagram along with corresponding input requirements. A limited study may be desirable for a variety of reasons, including budget and inventory constraints, or the need to obtain answers to very specific questions.

The methodology has been developed with as much capability as possible. However, there are certain areas where methods are limited. For example, the methodology calculates potential exposure to flood (e.g., dam break) or fire (following earthquake) in terms of the fraction of a geographical area that may be flooded or burned, but does not have methods for rigorous calculation of damage or loss due to flooding or fire. Consequently, these two potential contributors to the total loss would not be included in estimates of economic loss, casualties or loss of shelter.

A limiting factor in performing a study and quality of the inventory is the associated cost. Collection of inventory is without question the most costly part of performing the study. Furthermore, many municipalities have limited budgets for performing an earthquake loss estimation study. Thus, the methodology is structured to accommodate different users with different levels of resources.

While most users will develop a local inventory that best reflects the characteristics of their region, such as building types and demographics, the methodology is capable of producing crude estimates of losses based on a minimum of local input. Of course, the quality and uncertainty of the results is related to the detail of the inventory and the economic and demographic data provided. Crude estimates would most likely be used only as initial estimates to determine where more detailed analyses would be warranted.

At the other end of the spectrum, a user may wish to make detailed assessments of damage to and service outages for lifelines. Detailed analyses of lifelines require cooperation and input from utilities and transportation agencies. Lifeline systems require an understanding of the interactions between components and the potential for alternative pathways when certain components fail. Thus, without cooperation of utilities, the user is limited in the quality of analysis that can be performed.

The proposed loss estimation methods are capable of providing estimates of damage to and service outages for lifelines with a minimum of cooperation from lifeline operators. These estimates, of course, will have a great deal of uncertainty associated with them. However, they will be useful for planning purposes and for an initial estimate to determine where more detailed analyses would be warranted. Many lifeline operators perform their own detailed earthquake loss studies that incorporate detailed models of their systems.

Three types of analysis are defined to describe implementation of the methodology by users with different needs and resources. These types and their definitions are somewhat arbitrary, and the boundaries between the three types are not well defined. The three types are defined as follows:

Default Data Analysis: This is the simplest type of analysis requiring minimum effort by the user as it is based mostly on input provided with the methodology (e.g. census information, broad regional patterns of seismic code adoption and earthquake resistance of classes of construction, etc.). The user is not expected to have extensive technical knowledge. While the methods require some user-supplied input to run, the type of input required could be gathered by contacting government agencies or by referring to published information. At this level, estimates will be crude, and will likely be appropriate only as initial loss estimates to determine where more detailed analyses are warranted.

Some components of the methodology cannot be performed in a Default Data Analysis since they require more detailed inventory than that provided with the methodology. The following are not included in the Default Data Analysis: damage/loss due to liquefaction, landslide or surface fault rupture; damage/loss due to tsunamis, seiche or dam failure. At this level, the user has the option (not required) to enter information about hazardous substances and emergency facilities. One week to a month would be required to collect relevant information depending on the size of the region and the level of detail the user desires.

User-Supplied Data Analysis: This type of analysis will be the most commonly used. It requires more extensive inventory data and effort by the user than Default Data Analysis. The purpose of this type is to provide the user with the best estimates of earthquake damage/loss that can be obtained using the standardized methods of analysis included in the methodology. It is likely that the user will need to employ consultants to assist in the implementation of certain methods. For example, a local geotechnical engineer would likely be required to define soil and ground conditions.

All components of the methodology can be performed at this level and loss estimates are based on locally (user) developed inventories. At this level, there are standardized methods of analysis included in the software, but there is no standardized User-Supplied Data Analysis study. As the user provides more complete data, the quality of the analysis and results improve. Depending on the size of the region and the level of detail desired by the user, one to six months would be required to obtain the required input for this type of analysis.

Advanced Data and Models Analysis: This type incorporates results from engineering and economic studies carried out using methods and software not included within the methodology. At this level, one or more technical experts would be needed to acquire data, perform detailed analyses, assess damage/loss, and assist the user in gathering more extensive inventory. It is anticipated that at this level there will be extensive participation by local utilities and owners of special facilities. There is no standardized Advanced Data and Models Analysis study. The quality and detail of the results depend upon the level of effort. Six months to two years would be required to complete an Advanced Data and Models Analysis.

To summarize, User-Supplied Data Analysis and Advanced Data and Models Analysis represent a broad range of analyses, and the line between one type of analysis and another is fuzzy. The above definitions are provided to understand the scope and flexibility of the methodology, not to limit its application. The primary limit on the type of analysis will be the user's ability to provide required data.

Even with perfect data, which can never be obtained, the methodology would not be able to precisely estimate earthquake loss. Simply put, predictive methods are approximate and will often have large amounts of uncertainty associated with damage and loss estimates. A discussion of uncertainty and guidance for users performing earthquake loss estimation is provided in the *User Manual*.

Chapter 3
Inventory Data: Collection and Classification

3.1. Introduction

This chapter describes the classification of different buildings and lifeline systems, data and attributes required for performing damage and loss estimation, and the data supplied with the methodology. The different systems covered in this chapter include buildings and facilities, transportation systems, utility systems, and hazardous material facilities. In addition, census data, county business patterns, and indirect economic data are discussed. Sources and methods of collecting inventory data can be found in the User's Manual.

Required input data include both default data (data supplied with the methodology) and data that must be supplied by the user. Data supplied with the methodology include default values of classification systems (i.e., mapping relationships) and default databases (e.g., facility location, census information, and economic factors). Default data are supplied to assist the user that may not have the resources to develop inventory data and may be superseded by better information when the user can obtain such for the study region of interest.

3.2. Direct Damage Data - Buildings and Facilities

This section deals with the general building stock, essential facilities, and high potential loss facilities.

3.2.1. General Building Stock

The general building stock (GBS) includes residential, commercial, industrial, agricultural, religious, government, and educational buildings. The damage state probability of the general building stock is computed at the centroid of the census tract. The entire composition of the general building stock within a given census tract is lumped at the centroid of the census tract. The inventory information required for the analysis to evaluate the probability of damage to occupancy classes is the relationship between the specific occupancy class and the model building types. This can be computed directly from the specific occupancy class square footage inventory.

All three models (Earthquake, Wind and Flood) use key common data to ensure that the users do not have inventory discrepancies when switching from hazard to hazard. Generally the Earthquake Model and Hurricane display GBS data at the census tract level while the Flood Model displays GBS data at the census block.[1] The key GBS databases include the following:

- **Square footage by occupancy.** These data are the estimated floor area by specific occupancy (e.g., COM1). For viewing by the user, these data are also rolled up to the general occupancies (e.g., Residential).

- **Full Replacement Value by occupancy.** These data provide the user with estimated replacement values by specific occupancy (e.g., RES1). For viewing by the user, these data are also rolled up to the general occupancies (e.g., Commercial).

- **Building Count by occupancy.** These data provide the user with an estimated building count by specific occupancy (e.g., IND1). For viewing by the user, these data are also rolled up to the general occupancies (e.g., Government).

- **General Occupancy Mapping.** These data provide a general mapping for the GBS inventory data from the specific occupancy to general building type (e.g., Wood). [2]

- **Demographics.** This table provides housing and population statistics for the study region.

3.2.1.1. Classification

The purpose of a building inventory classification system is to group buildings with similar damage/loss characteristics into a set of pre-defined building classes. Damage and loss prediction models can then be developed for model building types which represent the average characteristics of the total population of buildings within each class.

The building inventory classification system used in this methodology has been developed to provide an ability to differentiate between buildings with substantially different damage and loss characteristics. The following primary parameters affecting building damage and loss characteristics were given consideration in developing the building inventory classification system.

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[1] In order to allow for future alignment between the Hurricane and Flood Models, the Hurricane Model will display and perform analysis at the census block level if the user has included the Flood Model in the study region.

[2] Generally, all three models will agree, however, a user can modify the general occupancy mapping at the census block level in the Flood Model thereby requiring them to select an “average” value at the tract level in the other two models, which will result in variances. This should not be an issue for users making this type of change.

- Structural parameters affecting structural capacity and response
  - Basic structural system (steel moment frame)
  - Building height (low-rise, mid-rise, high-rise)
  - Seismic design criteria (seismic zone) (Refer to Chapter 5)
- Nonstructural elements affecting nonstructural damage
- Occupancy (affecting casualties, business interruption and contents damage)
- Regional building practices (Refer to Chapter 5)
- Variability of building characteristics within the classification

To account for these parameters, the building inventory classification system consists of a two-dimensional matrix relating building structure (model building) types grouped in terms of basic structural systems and occupancy classes.

The basic model building types are based on FEMA-178 (FEMA, 1992) building classes. Building height subclasses were added to reflect the variation of typical building periods and other design parameters with building height. Mobile homes, which are not included in the FEMA-178 classification, were also added. A listing of structural building types, with corresponding labels, descriptions, and heights, is provided in Table 3.1.

The general building stock is also classified based on occupancy. The occupancy classification is broken into general occupancy and specific occupancy classes. For the methodology, the general occupancy classification system consists of seven groups (residential, commercial, industrial, religion/nonprofit, government, education and lifelines). There are 33 specific occupancy classes. The building occupancy classes are given in Table 3.2, where the general occupancy classes are identified in boldface. The distribution of specific occupancies classes within each general occupancy class can be computed for each census tract based on the occupancy square footage inventory (Section 3.6). These relationships are in a form shown in Table 3A.1 of Appendix 3A.

Table 3.1: Building Structure (Model Building) Types

No.	Label	Description	Height			
			Range		Typical	
			Name	Stories	Stories	Feet
1 2	W1 W2	**Wood, Light Frame (≤ 5,000 sq. ft.)** **Wood, Commercial and Industrial (> 5,000 sq. ft.)**		1 - 2 All	1 2	14 24
3 4 5	S1L S1M S1H	**Steel Moment Frame**	Low-Rise Mid-Rise High-Rise	1 - 3 4 - 7 8+	2 5 13	24 60 156
6 7 8	S2L S2M S2H	**Steel Braced Frame**	Low-Rise Mid-Rise High-Rise	1 - 3 4 - 7 8+	2 5 13	24 60 156
9	S3	**Steel Light Frame**		All	1	15
10 11 12	S4L S4M S4H	**Steel Frame with Cast-in-Place Concrete Shear Walls**	Low-Rise Mid-Rise High-Rise	1 - 3 4 - 7 8+	2 5 13	24 60 156
13 14 15	S5L S5M S5H	**Steel Frame with Unreinforced Masonry Infill Walls**	Low-Rise Mid-Rise High-Rise	1 - 3 4 - 7 8+	2 5 13	24 60 156
16 17 18	C1L C1M C1H	**Concrete Moment Frame**	Low-Rise Mid-Rise High-Rise	1 - 3 4 - 7 8+	2 5 12	20 50 120
19 20 21	C2L C2M C2H	**Concrete Shear Walls**	Low-Rise Mid-Rise High-Rise	1 - 3 4 - 7 8+	2 5 12	20 50 120
22 23 24	C3L C3M C3H	**Concrete Frame with Unreinforced Masonry Infill Walls**	Low-Rise Mid-Rise High-Rise	1 - 3 4 - 7 8+	2 5 12	20 50 120
25	PC1	**Precast Concrete Tilt-Up Walls**		All	1	15
26 27 28	PC2L PC2M PC2H	**Precast Concrete Frames with Concrete Shear Walls**	Low-Rise Mid-Rise High-Rise	1 - 3 4 - 7 8+	2 5 12	20 50 120
29 30	RM1L RM1M	**Reinforced Masonry Bearing Walls with Wood or Metal Deck Diaphragms**	Low-Rise Mid-Rise	1-3 4+	2 5	20 50
31 32 33	RM2L RM2M RM2H	**Reinforced Masonry Bearing Walls with Precast Concrete Diaphragms**	Low-Rise Mid-Rise High-Rise	1 - 3 4 - 7 8+	2 5 12	20 50 120
34 35	URML URMM	**Unreinforced Masonry Bearing Walls**	Low-Rise Mid-Rise	1 - 2 3+	1 3	15 35
36	MH	**Mobile Homes**		All	1	10

Table 3.2: Building Occupancy Classes

Label	Occupancy Class	Example Descriptions
	Residential	
RES1	Single Family Dwelling	House
RES2	Mobile Home	Mobile Home
RES3	Multi Family Dwelling RES3A Duplex RES3B 3-4 Units RES3C 5-9 Units RES3D 10-19 Units RES3E 20-49 Units RES3F 50+ Units	Apartment/Condominium
RES4	Temporary Lodging	Hotel/Motel
RES5	Institutional Dormitory	Group Housing (military, college), Jails
RES6	Nursing Home	
	Commercial	
COM1	Retail Trade	Store
COM2	Wholesale Trade	Warehouse
COM3	Personal and Repair Services	Service Station/Shop
COM4	Professional/Technical Services	Offices
COM5	Banks	
COM6	Hospital	
COM7	Medical Office/Clinic	
COM8	Entertainment & Recreation	Restaurants/Bars
COM9	Theaters	Theaters
COM10	Parking	Garages
	Industrial	
IND1	Heavy	Factory
IND2	Light	Factory
IND3	Food/Drugs/Chemicals	Factory
IND4	Metals/Minerals Processing	Factory
IND5	High Technology	Factory
IND6	Construction	Office
	Agriculture	
AGR1	Agriculture	
	Religion/Non/Profit	
REL1	Church/Non-Profit	
	Government	
GOV1	General Services	Office
GOV2	Emergency Response	Police/Fire Station/EOC
	Education	
EDU1	Grade Schools	
EDU2	Colleges/Universities	Does not include group housing

3.2.1.2. Specific Occupancy-to-Model Building Type Mapping

Default mapping schemes for specific occupancy classes (except for RES1) to model building types by floor area percentage are provided in Tables 3A.2 through 3A.16 of Appendix 3A. Table 3A.2 through 3A.10 provide the suggested mappings for the Western U.S. buildings and are based on information provided in ATC-13 (1985).

Tables 3A.11 through 3A.16 provide the mapping for buildings in the rest of the United States and are based on proprietary insurance data, opinions of a limited number of experts, and inferences drawn from tax assessors records. Table 3C.1 in Appendix 3C provides regional classification of the states. Table 3A.17 through 3A.21 provide model building distribution for the specific occupancy class “RES1” on a state-by-state basis. Tables 3A.2 through 3A.10 provide the mapping based on the height of buildings and the age of construction. The user must provide, for census tracts on the west coast, the proportion of buildings in low, mid, and high rise categories, and the proportion of buildings in the three categories according to age (pre- 1950, 1950-1970, and post 1970). These proportions are used to compute a weighted sum of matrices in Table 3A.2 through Table 3A.10 to arrive at the default specific occupancy class to model building type mapping. For the rest of the United States, Tables 3A.11 through 3A.16 provides the mapping based on the height of buildings only and the user must provide the proportion of buildings in low-, mid-, and high-rise categories to compute the default specific occupancy class to model building type mapping. The default mapping provided in Tables 3A.2 through 3A.16 should be considered as a guide: Accurate mapping may be developed based on the particular building type distribution within in the study region.

3.2.1.3. The Default General Building Stock Database

The general building stock inventory was developed from the following information:

- Census of Population and Housing, 2000: Summary Tape File 1B Extract on CD-ROM / prepared by the Bureau of Census.

- Census of Population and Housing, 2000: Summary Tape File 3 on CD-ROM / prepared by the Bureau of Census.

- Dun & Bradstreet, Business Population Report aggregated by Standard Industrial Classification (SIC) and Census Block, May 2002.

- Department of Energy, Housing Characteristics 1993. Office of Energy Markets and End Use, DOE/EIA-0314 (93), June 1995.

- Department of Energy, A Look at Residential Energy Consumption in 1997, DOE/EIA-0632(97), November 1999.

- Department of Energy, A Look at Commercial Buildings in 1995: Characteristics, Energy Consumption, and Energy Expenditures, DOE/EIA-0625(95), October 1998.

The US Census and the Dun & Bradstreet data were used to develop the general building stock inventory by Census Block and then rolled up to Census Tract. The three reports from the Department of Energy (DOE) helped in defining regional variations in characteristics such as number and size of garages, type of foundation, and number of stories. The inventory's baseline floor area is based on a distribution contained in the DOE's Energy Consumption Report. An approach was developed using the same report for determining the valuation of single-family residential homes by accounting for income as a factor on the cost of housing.

Initially the methodology created the opportunity for the user to develop conflicting or discrepant square footage totals for single-family residential structures within a census block between the inventory database and the valuation database. The solution was to integrate the regional DOE distributions with the income factors developed for determining valuation. To do this, default values for typical square footage per single-family home were developed from Energy Information Administration (EIA) data on heated floor space. These default data, shown in Table 3.3, are provided by region and income group. The breakdown reflects not only how typical housing size varies across the U.S., but also how in general, higher income areas tend to contain larger single-family homes.

Consequentially, the default typical square footage data was derived from a detailed, unpublished database provided by the EIA. Only information on families in single-family residences, aggregated across all foundation/basement types, was used. The raw database included information on the number of households by region, income category, and housing floor space. Regional data were available by 9 multi-state census divisions (e.g., New England).

The very nature of the default data, both in occupancy classifications and extent of coverage (national) requires the use of a baseline database collected in a consistent manner for the nation. The data source changes depending on the general use of the inventory being explored. For example, to determine the total floor area (square feet) of single-family residences by census block, one uses a data source like the Census data. While sufficient for residential occupancy, the Census data does not address non-residential occupancy classifications.

The development of the default inventory required two major datasets for the two main elements of the built environment. To create the default inventory for residential structures, the US Department of Commerce's Census of Housing was used. For commercial and industrial structures, a commercial supplier, Dun & Bradstreet (D&B) was contacted. The project team performed the aggregation to the census data, while D&B performed the aggregation to their own data (due to its proprietary nature).

The STF1B census extract at the census block level allows for the quick quantification of the single-family residential environment. When combined with the STF3A census extract at the census block group level, the STF1B can provide a better proxy of the multi-family environment than using one extract alone. In both the single-family and multi-family proxies, the proposed methodology represents an improvement over using single "average" values similar to the existing Hazus99 data.

The STF3A extract also provides information that is useful in developing distributions for the age of buildings within each census block group as well as valuable demographic data.

The D&B provides a realistic representation of the non-residential environment. Based on the site specific data contained within their database, D&B's data is used to provide a reasonable assessment of the non-residential environment. The processing of the D&B data is discussed in more detail in Section 3.2.1.4.

3.2.1.4. Specific Occupancy Square Footage

Single-Family Residences (RES1)

The following discussion highlights the data development effort for the RES1 square foot values by block. The Census Extract STF1B provides estimates of the single family attached and detached housing units on a block-by-block basis. Several other sources of information were used to develop distributions of square footage relative to the income of the census block group. The DOE distributions of income factors was used to develop a ratio of the census block group income (STF3A field P08A001) and the average income for the region (the nine multi-state census divisions).

The EIA data provided information regarding the heated floor area in relationship to income. Income was reported in 25 categories (e.g., $20,000-$22,499) that were converted into five relative income groups for consistency with the inventory valuation methodology. Housing floor space data were provided in 7 categories (e.g., 2,000-2,399 sq. ft.), which, for purposes of computing typical floor space, were represented by the midpoint of the range (e.g., 2,200 sq. ft.). This enabled average floor space to be calculated for the 9 census divisions and 5 relative income categories.

Table 3.3 Typical Square Footage Per Unit (Main Living Area) by Census Division (R)[1]

***R* = New England**

Income Ratio:	Basement	
	No (j=1)	*Yes[2] (j=2)*
$I_k < 0.5$	1300	975
$0.5 \leq I_k < 0.85$	1500	1125
$0.85 \leq I_k < 1.25$	1800	1350
$1.25 \leq I_k < 2.0$	1900	1425
$I_k \geq 2.0$	2200	1650

***R* = Middle Atlantic**

Income Ratio:	Basement	
	No (j=1)	*Yes[2] (j=2)*
$I_k < 0.5$	1300	975
$0.5 \leq I_k < 0.85$	1500	1125
$0.85 \leq I_k < 1.25$	1700	1275
$1.25 \leq I_k < 2.0$	1900	1425
$I_k \geq 2.0$	2200	1650

***R* = East North Central**

Income Ratio:	Basement	
	No (j=1)	*Yes[2] (j=2)*
$I_k < 0.5$	1300	975
$0.5 \leq I_k < 0.85$	1600	1200
$0.85 \leq I_k < 1.25$	1700	1275
$1.25 \leq I_k < 2.0$	1800	1350
$I_k \geq 2.0$	2500	1875

Table 3.3 Typical Square Footage Per Unit (Main Living Area) by Census Division (R)[1] (Continued)

***R* = West North Central**

Income Ratio:	Basement	
	No (j=1)	*Yes[2] (j=2)*
$I_k < 0.5$	1300	975
$0.5 \le I_k < 0.85$	1500	1125
$0.85 \le I_k < 1.25$	1800	1350
$1.25 \le I_k < 2.0$	1800	1350
$I_k \ge 2.0$	2300	1725

***R* = South Atlantic**

Income Ratio:	Basement	
	No (j=1)	*Yes[2] (j=2)*
$I_k < 0.5$	1400	1050
$0.5 \le I_k < 0.85$	1600	1200
$0.85 \le I_k < 1.25$	1700	1275
$1.25 \le I_k < 2.0$	2000	1500
$I_k \ge 2.0$	2300	1725

***R* = East South Central**

Income Ratio:	Basement	
	No (j=1)	*Yes[2] (j=2)*
$I_k < 0.5$	1300	975
$0.5 \le I_k < 0.85$	1400	1050
$0.85 \le I_k < 1.25$	1700	1275
$1.25 \le I_k < 2.0$	1900	1425
$I_k \ge 2.0$	2500	1875

***R* = West South Central**

Income Ratio:	Basement	
	No (j=1)	*Yes[2] (j=2)*
$I_k < 0.5$	1300	975
$0.5 \le I_k < 0.85$	1700	1275
$0.85 \le I_k < 1.25$	1800	1350
$1.25 \le I_k < 2.0$	1900	1425
$I_k \ge 2.0$	2500	1875

Table 3.3 Typical Square Footage Per Unit (Main Living Area) by Census Division (R)[1] (Continued)

***R* = Mountain**

Income Ratio:	Basement	
	No (j=1)	***Yes[2] (j=2)***
$I_k < 0.5$	1200	900
$0.5 \leq I_k < 0.85$	1500	1125
$0.85 \leq I_k < 1.25$	1700	1275
$1.25 \leq I_k < 2.0$	1800	1350
$I_k \geq 2.0$	2600	1950

***R* = Pacific**

Income Ratio:	Basement	
	No (j=1)	***Yes[2] (j=2)***
$I_k < 0.5$	1300	975
$0.5 \leq I_k < 0.85$	1500	1125
$0.85 \leq I_k < 1.25$	1700	1275
$1.25 \leq I_k < 2.0$	1900	1425
$I_k \geq 2.0$	2100	1575

Notes:

1 *Based on data from the Energy Information Administration, Housing Characteristics 1993;*

2 *(Area of main living area if basement present) = 0.75 x (Area of main living area if no basement). This adjustment allows consistent application of the Means cost models, in which basement areas are added-on, and are assumed to be 1/3 of main living area.*

While the US Census data does have data defining the median income for each census block, there is data for the median income for each census block group. This value will be applied to each block within the block group. With the a median income for each census block, and the median income for the census region, it is possible to define an Income Ratio that can be used to determine the square footage for buildings with and without basements. Table 3.4 below shows the 9 census regions, the states within those regions and the values used to compute the Income Ratio. The value from the Census STF3A field P08A001 is the median income for the census block group that will be applied to every census block within the group. The distribution of basements is a summation or roll-up of the foundation type distribution discussed later in this section.

Table 3.4 Income Ratio and Basement Distribution by Census Region

Region (States)	Income Ratio	Percent with Basement	Percent without Basement
AL	P053001 / 36,268	25	75
AK	P053001 / 52,492	13	87
AZ	P053001 / 39,653	32	68
AR	P053001 / 30,082	5	95
CA	P053001 / 45,070	13	87
CO	P053001 / 49,216	32	68
CT	P053001 / 50,647	81	19
DE	P053001 / 47,438	23	77
DC	P053001 / 38,005	23	77
FL	P053001 / 37,305	23	77
GA	P053001 / 41,481	23	77
HI	P053001 / 45,657	13	87
ID	P053001 / 37,760	32	68
IL	P053001 / 46,649	68	32
IN	P053001 / 41,315	68	32
IA	P053001 / 41,560	75	25
KS	P053001 / 38,393	75	25
KY	P053001 / 36,826	25	75
LA	P053001 / 32,500	5	95
ME	P053001 / 39,815	81	19
MD	P053001 / 52,846	23	77
MA	P053001 / 45,769	81	19
MI	P053001 / 46,034	68	32
MN	P053001 / 50,088	75	25
MS	P053001 / 31,963	25	75
MO	P053001 / 44,247	75	25
MT	P053001 / 32,553	32	68
NE	P053001 / 39,029	75	25
NV	P053001 / 43,262	32	68
NH	P053001 / 48,029	81	19
NJ	P053001 / 51,739	76	24
NM	P053001 / 34,035	32	68
NY	P053001 / 40,822	76	24
NC	P053001 / 38,413	23	77
ND	P053001 / 33,769	75	25

Table 3.4 Income Ratio and Basement Distribution by Census Region (Continued)

Region (States)	Income Ratio	Percent with Basement	Percent without Basement
OH	P053001 / 41,972	68	32
OK	P053001 / 34,020	5	95
OR	P053001 / 41,915	13	87
PA	P053001 / 41,394	76	24
RI	P053001 / 43,428	81	19
SC	P053001 / 36,671	23	77
SD	P053001 / 35,986	75	25
TN	P053001 / 35,874	25	75
TX	P053001 / 39,296	5	95
UT	P053001 / 46,539	32	68
VT	P053001 / 40,908	81	19
VA	P053001 / 47,701	23	77
WA	P053001 / 46,412	13	87
WV	P053001 / 29,217	23	77
WI	P053001 / 45,441	68	32
WY	P053001 / 38,291	32	68

Once the parameters above had been defined, it is possible to develop an algorithm that allows for the estimation of the RES1 or single-family residential square footage for the entire nation. This algorithm is:

RES1 (sq. ft.) = Total Single Family Units (STF1B H1BX0002) *[(Percent of units with basement) * (floor area w/basement based on income ratio and region) + (Percent of units without basement)*(floor area w/o basement based on income ratio and region]

where Income Ratio = STF3A P08A001/regional income

For a sample New England census block, 81% Basement 19% no basement and an I_k of 0.67:

RES1 (sq. ft.) = [STF1BX0002] * [(0.81)*(1,125) + (0.19)*(1,500)]

Multi-Family and Manufactured Housing (RES3 and RES2)

Developing the multi-family (RES3A through RES3F) and manufactured housing (RES2) inventory requires additional information and effort compared to the single-family occupancy classification. In the 1999 census extract, the STF1B (census block data) extract identifies only those housing units within the 10 or more unit classification, unfortunately, the 2000 census extract no longer provided that information. Therefore in order to define of the multi-family units, it is necessary to utilize the STF3A extract. The multi-family definition in the STF3A extract identifies Duplex, 3-4 Unit, 5-9 unit, 10-19 unit, 20-49 unit, and 50+ dwellings. Additionally the STF3A census data provides a definition of the Manufactured Housing (MH) units within a block group and therefore the RES2 was processed at the same time. The census data has an "other" classification for that will be ignored since this classification represent a very small portion of the universe of housing units and there is no "other" damage functions that can be assigned to these facilities. Examples of the "Other" Census classification include vans and houseboats.

Unlike the single family residential that used the Housing Characteristics 1993 to define heated floor area, assessor data from around the United States, including that from the six Proof-of-Concept (POC) communities, was reviewed to develop preliminary estimates of average floor area for multi-family housing. This data was then peer reviewed by engineering experts to develop an average floor area per number of units for the unit ranges provided by the census data. Table 3.5 shows the distribution of the floor area by unit. The associated equations provide an example of the calculations that have taken place.

Table 3.5 Floor Areas for Multi-Family Dwellings (RES2 & RES3A-RES3F)

Units	Duplex	3-4	5-9	10-19	20-49	50+	Manufactured Housing	Other
Floor Area	1,500	750	800	750	700	650	Single Wide – 950 Double Wide – 1,350	NA

Previously, the flood model team had a complex process that allowed for a more accurate block level distribution. However, when the US Census Bureau modified the SF1 extract to eliminate information regarding the single-family and large multi-family fields, it became necessary to modify the data manipulation process. The multi-family data was still available in the SF3 extract at the census block group level. The only available process was to distribute the census block group data homogeneously throughout the census blocks. The distribution process is facilitated by finding the ratio of total housing units per census block (H1BX0001) with respect to the total housing units per census block group (H0010001). This ratio was then used to as a multiplier to distribute the census block group level multi-family data into each census block.

Step 1: Develop the ratio of total housing units for each census block"

Unit Ratio = (H1BX0001)/(H0010001)

Step 2: Distribute the multi-family housing units throughout each census block

For example:

Duplex units per block = H0200003*Unit Ratio

Step 3: Derive Floor area per occupancy classification

Manufactured Housing (sq. ft.) = Census Block RES2 (from Step 2)* (0.75 * 950 + 0.25 * 1,400)

Duplex (sq. ft.) = (Census Block Duplex from Step 2) * 1,500

3-4 Units (sq. ft.) = (Census Block 3-4 units from Step 2) * 750

5-9 Units (sq. ft.) = (Census Block 5-9 units from Step 2) * 800

10-19 Units (sq. ft.) = (Census Block 10-19 units from Step 2) * 750

20-49 Units (sq. ft.) = (Census Block 20-49 units from Step 2) * 700

50+ Units (sq. ft.) = (Census Block 50+ units from Step 2) * 700

By using the above distribution, the valuation can be more specifically tailored to each floor plan. This has the potential future benefit of allowing the user to modify the floor area for multi-family units. For example in future releases, it may be possible to provide the user the capability to modify the average floor area for duplexes to 2,000 Sq Ft per unit if this more closely reflected the users community. This should then lead to a net decrease in the total number of units for the RES3A occupancy classification.

The floor areas presented for manufactured housing are based on review of various internet websites for manufactured housing sales (new and used), housing manufacturers, and finally additional US Census Bureau data. There was a great deal of information regarding sales and shipment of manufactured housing since the 1970's, but there was very little information regarding the attrition rate experienced over the same 30-year span. Charting information from the Manufactured Housing Institute, Figure 3.1 shows that there has been a general growth trend in the size of the units since the 1980's for both the single wide and doublewide (also known as single-section and multi-section) manufactured housing.

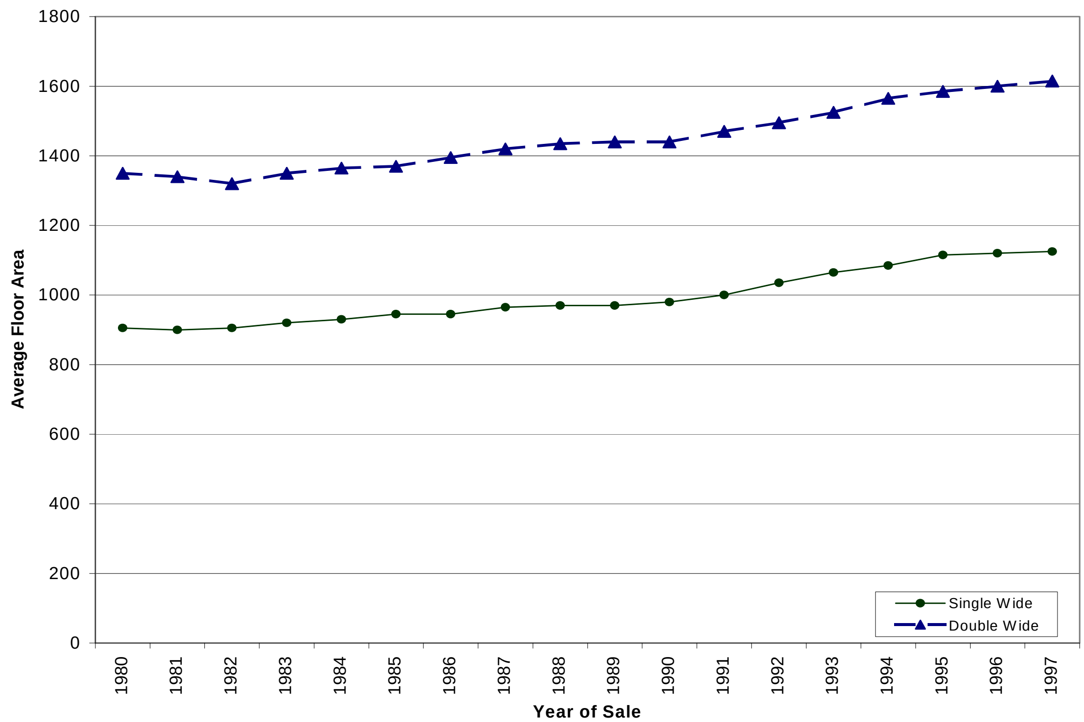

Figure 3.1 Manufactured Housing Growth Over Time

The recently released American Housing Survey for the US, 1997[3] (September, 1999) contained estimated floor areas for manufactured housing (labeled Mobile Home in the Census tables) based on a surveyed population of over 8 million manufactured homes across the United States. The survey does not differentiate between single-section and multi-section units, but when the values are charted the distribution presents natural points to estimate these dimensions. Figure 3.2 shows the distribution of floor area by number of structures from the survey. Using this distribution, it is possible to estimate representative values for single-section and multi-section units of 950 Square Feet and 1,400 Square Feet respectively.

3 US Department of Housing and Urban Development and US Census Bureau, American Housing Survey for the United States H150/97, Office of Policy Development an Research and the US Census Bureau, September 1999.

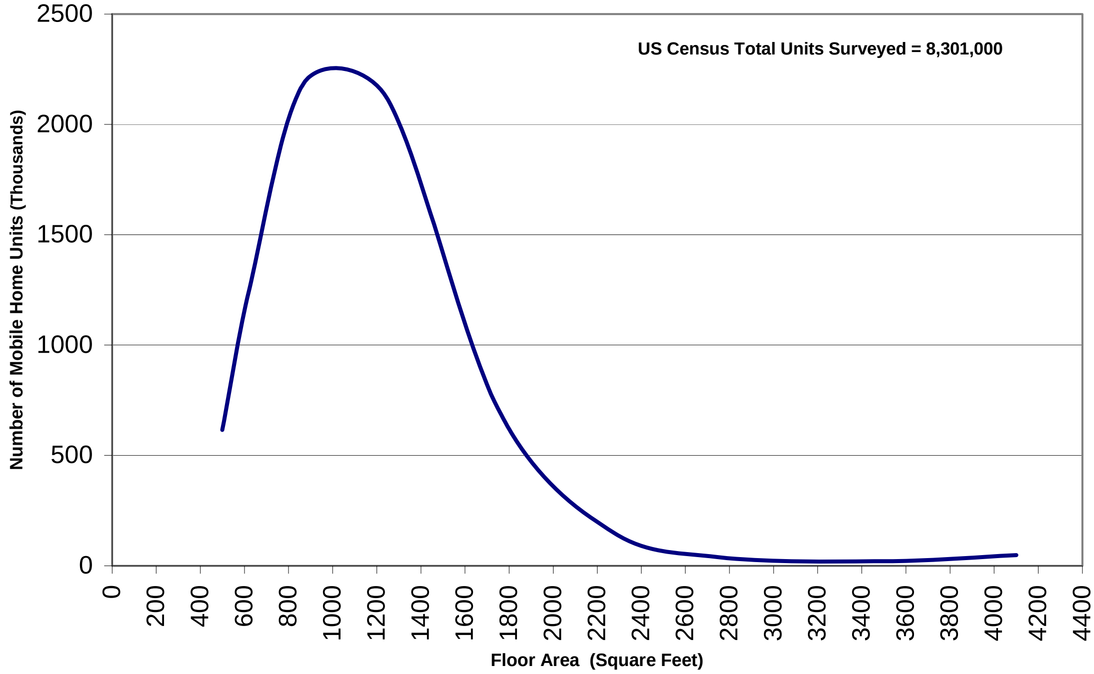

Figure 3.2 Number of Mobile Home Units by Floor Area – 1990 US Census Data Housing Characteristics

Non-Residential Occupancy Classifications

The Hazus99 Earthquake Model inventory used the D&B business inventory at the census tract level for all non-residential structures and those facilities that are commercial in nature but provide housing for people such as hotels (RES4) and nursing homes (RES6). The D&B data represents approximately 76 percent (approximately 14 million) of the total estimated businesses in the United States (approximately 19 million). While initially this might seem like a low representation, the D&B database accounts for 98 percent of the gross national product. D&B states that the remaining businesses are likely to be smaller and home-based. If true, the proxy inventory established for the residential dwellings will account for these businesses in the total damage estimates.

D&B provided the data aggregated on the SIC definitions used previously in the development of the Hazus99 Earthquake Model (Hazus99 Users Manual, 1997 Table Appendix A.19, page A-23). The D&B data obtained for the Flood Model provided floor area for businesses at the census block level. It should be noted that D&B performs regular random sampling of businesses in their database to obtain the actual floor area. D&B then utilizes proprietary algorithms to estimate the floor area for the remaining businesses. According to D&B, floor area is sampled for approximately 25 percent of their business database and the remainder is modeled.

With their data, D&B provided a count of businesses, the total floor area (modeled and sampled), and the total number of employees. During a review of the data, it was discovered that D&B had some data aggregated at the census block groups and tracts level. Review of the data determined that these errors were consistent with automated georeferencing processes and are likely to represent those businesses where the addresses did not match directly with D&B's reference street base. D&B performed an additional review and ascertained that this was in fact the cause of this aggregation. It was felt, however, that the tract and block group data could be safely distributed to the census blocks based on weighted averages of commercial development within the blocks. Review of the results of this effort showed little net impact and continued agreement with ground truth data.

The D&B data contained information on all non-residential uses including some agricultural facilities, general government offices, schools, and churches. Again, comparison with POC data and other available data showed relatively good agreement.

3.2.1.5. Building Replacement Costs

Building replacement cost models within Hazus are based on industry-standard cost-estimation models published in Means Square Foot Costs (R.S. Means, 2002). Replacement cost data are stored within Hazus at the census tract and census block level for each occupancy class. For each Hazus occupancy class, a basic default structure full replacement cost model (cost per square foot) has been determined, and are provided in Table 3.6. Commercial and industrial occupancies have a typical building replacement cost model associated with each occupancy class (e.g., COM4, Professional/Technical/Business Services, is represented by a typical, 80,000 square foot, 5 to 10 story office building). In most cases, the typical building chosen to represent the occupancy class is the same as was used in the original Hazus earthquake model (based on Means, 1994), except for single family residential, multi-family residential, and industrial uses. Both primary default (in bold) and alternate models (in italics) are provided in the table. As shown, in some cases the alternate costs are very similar to the primary default cost (e.g., medium and large dormitories), although a number of alternate costs vary quite a bit (medium hotel vs. medium motel). Square foot costs presented in the table have been averaged over the various alternatives for exterior wall construction (e.g., wood siding over wood frame, brick veneer over wood frame, stucco on wood frame or precast concrete, concrete block over wood joists or precast concrete, etc.). For non-residential structures, the default configuration assumes structures without basements.

The RES1 (single family residential) replacement cost model is the most complex, utilizing socio-economic data from the census to determine an appropriate mix of construction classes (Economy, Average, Custom and Luxury) and associated replacement cost models. The algorithm is described in Section 3.2.1.5.1.4. Within Means, basements are not considered in the base cost of the structure and are handled as an additive adjustment (additional cost per square foot of main structure). Table 3.7 provides Means (2002) replacement costs for the various single family dwelling configurations available in the default building inventory (1, 2, and 3 story and split-level), assuming a typical size of 1,600 square feet. Costs have been averaged for the various alternatives for exterior wall construction.

Because the default single family residential (SFR) damage model is based on the FIA credibility-weighted depth damage functions, whose coverage extends to garages, the replacement cost of garages will also be included in the basic replacement cost. Relevant Means models for SFR garages include costs by construction class (economy, average, custom, and luxury), for detached and attached 1-car, 2-car and 3-car garages, constructed of wood or masonry. For incorporation into Hazus, costs by size and construction class have been averaged for attached/detached and various materials. Average costs associated with garage types included in the default inventory for single family residential structures (1-car, 2-car and 3-car) were provided in Table 3.8.

3.2.1.5.1. Single-Family Residential Valuation Algorithm

The algorithm defined below will be used to develop the valuation for single-family residential buildings at the census block level. This algorithm utilizes socio-economic data from the census to derive an appropriate Means-based cost for each census block. The earthquake and wind models shall use a “roll-up” of the results from the flood model calculations. Some round-off error will occur, but this cannot be avoided.

The valuation algorithm can be summarized mathematically in equation (1) below:

$$V_{RES1,\,k} = (A_{RES1,\,k})*[\sum_{i=1}^{4} \sum_{j=1}^{4} w_{i,k}*w_{j,k}*C_{i,j}] + (A_{RES1,\,k})*w_{l,k}*[\sum_{i=1}^{4} \sum_{j=1}^{4} ?w_{i,k}*w_{j,k}*C_{i,j,l}]$$

$$+(RES1Cnt_{\,k})*[\sum_{i=1}^{4} ?\sum_{j=1}^{4} w_{i,k}*w_{m,k}*C_{i,\,m}] \qquad (3\text{-}1)$$

Where:

$V_{RES1,\,k}$	is the total estimated valuation for single-family residences (RES1) for a given census block (k). $V_{RES1,\,k}$ is editable when viewing the dollar exposure by specific occupancy table.

$A_{RES1,k}$	is the total single-family residential (RES1) floor area (square feet) for a given census block (k) found in the square foot by specific occupancy table. $A_{RES1,k}$ is editable when viewing the square foot by specific occupancy table.
i	the Means construction class (1 = Economy, 2 = Average, 3 = Custom, 4 = Luxury).
$w_{i,k}$	is the weighting factor for the Means construction class (i) for the given census block (k) and is determined from the income ratio range as shown in Table 14.4 below. Values are displayed in percent to the user and are editable when viewing the dollar exposure parameters tables.
j	the number of stories class for single-family (RES1) structures (1 = 1-story, 2 = 2-story, 3 = 3-story, and 4 = split level)
$w_{j,k}$	is the weighting factor for the Number of Stories class (j) for the given census block (k) depending on the census region of that block (by state FIPS). Weighting factors were developed from regional construction type distributions as discussed in Section 3. Values are displayed in percent to the user and are editable when viewing the dollar exposure parameters tables.
$C_{i,j}$	is the single-family (RES1) cost per square foot for the given Means construction class (i) and number of stories class (j). RES1 replacement costs are seen in the third column of Table 14.2. Values are editable when viewing the dollar exposure parameters tables.
l	the basement status available for single-family residences (1 = yes, 2 = no).
$w_{l,k}$	is the weighting factor for basements for the given census block (k) depending on the census region of that block (by state FIPS). Weighting factors were developed from regional foundation type distributions as discussed in Section 3. Values are displayed in

percent to the user and are editable when viewing the dollar exposure parameters tables. Default will be established based on whether the block is a coastal or non-coastal block.

$C_{i,j,l}$ the additional cost, per square foot of the main structure, for a finished basement for the given Means construction class (i) and number of stories class (j), as shown in Table 14.2, Column 4. Note: $C_{i,j,l} = 0$ when l = 2. Values are editable when viewing the dollar exposure parameters tables.

m the garage combinations available for single-family residences (1 = 1-car, 2 = 2-car, 3 = 3-car, 4 = carport, and 5 = none).

$w_{m,k}$ is the weighting factor for the garage type (m) for the given census block (k) depending on the census region of that block (by state FIPS). Weighting factors were developed from regional construction type distributions as discussed in Section 3. Values are displayed in percent to the user and are editable when viewing the dollar exposure parameters tables.

$C_{i,m}$ the additional replacement cost for a given garage type (m), for the given Means construction class (i) as shown in Table 14.3. Note: $C_{i,m} = 0$ when m = 4 (covered carport) or m = 5 (none). Values are editable when viewing the dollar exposure parameters table.

R_{ES1Cnt} the count of RES1 structures within the given census block (k) taken directly from the Building Count by occupancy table.

As the algorithm shows, the basic replacement cost per square foot is a function of the Means construction class, the number of stories and an additional cost per square foot of the main structure for the existence of a finished or unfinished basement. Finally, there is an additional cost per housing unit based on the garage associated with the structure. The valuation parameters are presented in a series of tables in Section 3.2.1.5.1.4 of this document.

3.2.1.5.2. Manufactured Housing Valuation Algorithm

It is necessary to clarify that RES2 within Hazus99 and Hazus$^{®MH}$, while designated Manufactured Housing, represents Mobile Homes and not single-family premanufactured housing. The US Census provides a detailed count of the mobile homes within each census block and this quantity is used to develop the total floor area (square foot) of the RES2 occupancy classification. The total floor area was developed assuming a typical floor area and average distribution of singlewide to doublewide mobile homes. Unlike other occupancy classifications, there are no allowances for variation of floor heights (number of stories) or other valuation parameters. The valuation of manufactured housing is the straight multiplication of the total floor area by the baseline replacement cost per square foot. The cost per square foot (C_{RES2}) is defined in Table 3.6 in the valuation parameters section (Section 3.2.1.5.1.4) of this document

The algorithm for manufactured housing is defined in equation (2) below:

$$V_{RES2,k} = A_{RES2,k} * C_{RES2} \tag{3-2}$$

Where:

$V_{RES2,k}$ is the total estimated valuation for Manufactured Housing (RES2) for a given census block (k). $V_{RES2,\,k}$ is editable when viewing the dollar exposure by specific occupancy table.

$A_{RES2,k}$ is the total Manufactured Housing (RES2) floor area (square feet) for a given census block (k) found in the square foot by specific occupancy table. $A_{RES2,k}$ is editable when viewing the square foot by specific occupancy table.

C_{RES2} is the Manufactured Housing (RES2) cost per square foot. RES2 replacement costs are Table 14.1 ($30.90/SqFt). The value is editable when viewing the dollar exposure parameters tables.

The flood model has accounted for differential areas between singlewide and doublewide manufactured housing in the total floor area, it is assumed that the cost per square foot does not vary greatly between the two structure types.

3.2.1.5.3. Other Residential and Non-Residential Occupancies

The algorithm for the remaining residential occupancies (RES3-RES6) and all non-residential (COM, IND, EDU, REL, GOV, and AGR) occupancies is not as complex as the single family model but allows for the potential incorporation of a distribution for number of stories. It should be noted that the replacement costs seen in Table 3.6 are an average replacement cost by occupancy. In other words, the replacement cost is averaged across structure types, stories and construction classes to produce the values in Table 14.1.

The algorithm for the remaining residential occupancies and non-residential occupancies can be seen in equation (3) below:

$$V_{x,k} = \sum A_{x,k} * C_x \tag{3-3}$$

Where:

x	defines the remaining occupancy classifications (x ranges from 3 to 28 for the remaining occupancies, i.e., RES5, COM1, REL1, etc.) for which the cost is being calculated.
$V_{x,k}$	is the total estimated valuation for the specific occupancy (x) (such as RES4, COM3, or IND6) for a given census block (k). $V_{x,k}$ is editable when viewing the dollar exposure by specific occupancy table.
$A_{x,k}$	is the total floor area (square feet) for a specific occupancy (x) (such as RES3, COM8, IND4, GOV1, etc.) for a given census block (k) found in the square foot by specific occupancy table. $A_{x,k}$ is editable when viewing the square foot by specific occupancy table.
C_x	is the cost per square foot for the specific occupancy (x). The replacement costs are seen in Table 14.1 below by specific occupancy. Values are editable when viewing the dollar exposure parameters tables.

At this time, the flood model depreciation models for non-single-family residential structures will not depend on features such as the number of stories. A distribution of number of stories will still be developed in the dollar exposure parameters table since the creation of such depreciation models are seen as a potential enhancement in future versions of the Hazus Flood Model.

3.2.1.5.4. Valuation Tables

The following tables present the baseline valuation parameters for the variables discussed in Section 14.4 of this document. Each of these parameters is editable by the user.

Table 3.6 Default Full Replacement Cost Models (Means, 2002)

Hazus Occupancy Class Description		Sub-category	Means Model Description (Means Model Number)	Means Cost/SF (2002)
RES1	Single Family Dwelling	See Table 14.2		
RES2	Manufactured Housing	Manufactured Housing	Manufactured Housing (N/A)[1]	$30.90
RES3	Multi Family Dwelling – small	Duplex	SFR Avg 2 St., MF adj, 3000 SF	$67.24
		Triplex/Quads	SFR Avg 2 St., MF adj, 3000 SF	$73.08
	Multi Family Dwelling – medium	5-9 units	Apt, 1-3 st, 8,000 SF (M.010)	$125.63
		10-19 units	Apt., 1-3 st., 12,000 SF (M.010)	$112.73
	Multi Family Dwelling – large	20-49 units	Apt., 4-7 st., 40,000 SF (M.020)	$108.86
		50+ units	Apt., 4-7 st., 60,000 SF (M.020)	$106.13
			Apt., 8-24 st., *145,000 SF* (M.030)	$111.69
RES4	Temp. Lodging	Hotel, medium	Hotel, 4-7 st., 135,000 SF(M.350)	$104.63
		Hotel, large	Hotel, 8-24 st., 450,000 SF (M.360)	$93.47
		Motel, small	Motel, 1 st., 8,000 SF (M.420)	$94.13
		Motel, medium	Motel, 2-3 st., *49,000 SF* (M.430)	$110.03
RES5	Institutional Dormitory	Dorm, medium	College Dorm, 2-3 st, *25,000 SF* (M.130)	$118.82
		Dorm, large	College Dorm, 4-8 st, *85,000 SF* (M.140)	$113.31
		Dorm, small	Frat House, 2 st., 10,000 SF (M.240)	$99.50
RES6	Nursing Home	Nursing home	Nursing Home, 2 st., 25,000 SF (M.450)	$104.62
COM1	Retail Trade	Dept Store, 1 st	Store, Dept., 1 st., 110,000 SF (M.610)	$71.54
		Dept Store, 3 st	Store, Dept., 3 st., 95,000 SF (M.620)	$88.73
		Store, small	Store, retail, 8,000 SF (M.630)	$79.23
		Store, medium	Supermarket, *44,000 SF* (M.640)	$69.09
		Store, convenience	Store, Convenience, 4,000 SF (M.600)	$83.59
		Auto Sales	Garage, Auto Sales, 21,000 SF (M.260)	$70.84
COM2	Wholesale Trade	Warehouse, medium	Warehouse, 30,000 SF (M.690)	$61.91
		Warehouse, large	Warehouse, 60,000 SF (M.690)	$56.58
		Warehouse, small	Warehouse, 15,000 SF (M.690)	$70.43
COM3	Personal and Repair Services	Garage, Repair	Garage, Repair, *10,000 SF* (M.290)	$86.81
		Garage, Service sta.	Garage, Service sta., 1,400 SF (M.300)	$113.91
		Funeral Home	Funeral home, 10,000 SF (M.250)	$97.66
		Laundromat	Laundromat 3,000 SF (M.380)	$135.64
		Car Wash	Car Wash, 1 st., 800 SF (M.080)	$198.28

COM4	Prof./ Tech./Business Services	Office, Medium	Office, 5-10 st., *80,000 SF* (M.470)	$98.96
		Office, Small	Office, 2-4 st., *20,000 SF* (M.460)	$102.69
		Office, Large	Office, 11-20 st., *260,000 SF* (M.480)	$88.21
COM5	Banks	Bank	Bank, 1 st., 4100 SF (M.050)	$153.97

Table 3.6 Default Full Replacement Cost Models (Means, 2002) (Continued)

Hazus Occupancy Class Description		Sub-category	Means Model Description (Means Model Number)	Means Cost/SF (2002)
COM6	Hospital	Hospital, Medium	Hospital, 2-3 st., 55,000 SF (M.330)	$144.60
		Hospital, Large	Hospital, 4-8 st., 200,000 SF (M.340)	$125.60
COM7	Medical Office/Clinic	Med. Office, medium	Medical office, 2 st., 7,000 SF (M.410)	$129.82
		Med. Office, small	Medical office, 1 st., 7,000 SF (M.400)	$118.01
COM8	Entertainment & Recreation	Restaurant	Restaurant, 1 st., 5,000 SF (M.530)	$137.02
		Restaurant, Fast food	Restaurant, fast food, 4,000 SF (M.540)	$121.49
		Bowling Alley	Bowling Alley, 20,000 SF (M.060)	$72.31
		Country Club	Club, Country, 1 st., 6,000 SF (M.100)	$135.23
		Social Club	Club, Social, 1 st., 22,000 SF (M.110)	$95.39
		Racquetball Court	Racquetball Court, 30,000 SF (M.510)	$111.23
		Hockey Rink	Hockey Rink 30,000 SF (M.550)	$115.13
COM9	Theaters	Movie Theatre	Movie Theatre, 12,000 SF (M.440)	$102.35
		Auditorium	Auditorium, 1 st., 24,000 SF (M.040)	$109.60
COM10	Parking	Parking Garage	Garage, Pkg, 5 st., 145,000 SF (M.270)	$34.78
		Parking Garage, Underground	Garage, UG Pkg, 100,000 SF (M.280)	$49.20
IND1	Heavy	Factory, small	Factory, 1 st., 30,000 SF (M.200)	$73.82
		Factory, large	Factory, 3 st., 90,000 SF (M.210)	$78.61
IND2	Light	Warehouse, medium	Warehouse, 30,000 SF (M.690)	$61.91
		Factory, small	Factory, 1 st., 30,000 SF (M.200)	$73.82
		Factory, large	Factory, 3 st., 90,000 SF (M.210)	$78.61
IND3	Food/Drugs/Chemicals	College Laboratory	College Lab, 1 st., 45,000 SF (M.150)	$119.51
		Factory, small	Factory, 1 st., 30,000 SF (M.200)	$73.82
		Factory, large	Factory, 3 st., 90,000 SF (M.210)	$78.61
IND4	Metals/Minerals Processing	College Laboratory	College Lab, 1 st., 45,000 SF (M.150)	$119.51
		Factory, small	Factory, 1 st., 30,000 SF (M.200)	$73.82
		Factory, large	Factory, 3 st., 90,000 SF (M.210)	$78.61
IND5	High Technology	College Laboratory	College Lab, 1 st., 45,000 SF (M.150)	$119.51
		Factory, small	Factory, 1 st., 30,000 SF (M.200)	$73.82
		Factory, large	Factory, 3 st., 90,000 SF (M.210)	$78.61
IND6	Construction	Warehouse, medium	Warehouse, 30,000 SF (M.690)	$61.91
		Warehouse, large	Warehouse, 60,000 SF (M.690)	$56.58
		Warehouse, small	Warehouse, 15,000 SF (M.690)	$70.43
AGR1	Agriculture	Warehouse, medium	Warehouse, 30,000 SF (M.690)	$61.91
		Warehouse, large	Warehouse, 60,000 SF (M.690)	$56.58
		Warehouse, small	Warehouse, 15,000 SF (M.690)	$70.43
REL1	Church	Church	Church, 1 st., 17,000 SF (M.090)	$114.08

Table 3.6 Default Full Replacement Cost Models (Means, 2002) (Continued)

Hazus Occupancy Class Description		Sub-category	Means Model Description (Means Model Number)	Means Cost/SF (2002)
GOV1	General Services	Town Hall, small	Town Hall, 1 st., 11,000 SF (M.670)	$90.30
		Town Hall, medium	Town Hall, 2-3 st., 18,000 SF (M.680)	$112.94
		Courthouse, small	Courthouse, 1 st., 30,000 SF (M.180)	$130.71
		Courthouse, medium	Courthouse, 2-3 st., 60,000 SF (M.190)	$136.81
		Post Office	Post Office, 13,000 SF (M.500)	$86.83
GOV2	Emergency Response	Police Station	Police Station, 2 st., 11,000 SF (M.490)	$136.10
		Fire Station, small	Fire Station, 1 st., 6,000 SF (M.220)	$105.53
		Fire Station, medium	Fire Station, 2 st., 10,000 SF (M.230)	$110.34
EDU1	Schools/Libraries	High School	School, High, 130,000 SF (M.570)	$92.80
		Elementary School	School, Elementary, 45,000 SF (M.560)	$90.22
		Jr. High School	School, Jr. High, 110,000 SF (M.580)	$95.21
		Library	Library, 2 st., 22,000 SF (M.390)	$103.94
		Religious School	Religious Educ, 1 st., 10,000 SF (M.520)	$112.19
EDU2	Colleges/Universities	College Classroom	College Class. 2-3 st, *50,000 SF* (M.120)	$114.68
		College Laboratory	College Lab, 1 st., 45,000 SF (M.150)	$119.51
		Vocational school	School, Vocational, 40,000 SF (M.590)	$93.96

Notes:

1 Manufactured Housing Institute, 2000 cost for new manufactured home

Table 3.7 Replacement Costs (and Basement Adjustment) for RES1 Structures by Means Constructions Class (Means, 2002)

Means Construction Class	Height Class	Average Base cost per square foot	Adjustment for Finished Basement (cost per SF of main str.)	Adjustment for Unfinished Basement (cost per SF of main str.)
Economy	1 story	55.23	16.95	6.35
	2 story	59.58	9.85	4.20
	3-story	N/A – use 2 st	N/A – use 2 st	N/A – use 2 st
	Split level*	55.30	12.32	5.02
Average	1 story	79.88	21.15	7.35
	2 story	79.29	13.80	4.85
	3-story	84.81	10.97	3.78
	Split level	74.94	16.42	5.77
Custom	1 story	99.59	31.90	11.65
	2 story	99.63	18.75	7.15
	3-story	105.83	13.78	5.35
	Split level	93.81	23.35	8.78
Luxury	1 story	122.25	37.75	13.20
	2 story	117.55	22.35	8.10
	3-story	124.00	16.48	6.05
	Split level	111.13	27.82	9.95

Table 3.8 Single Family Residential Garage Adjustment (Means, 2002)

Means Construction Class	Garage Type	Average Additional Garage Cost per Residence
Economy	1 car	$10,700
	2 car	$16,700
	3 car	$22,600
Average	1 car	$11,000
	2 car	$17,100
	3 car	$23,000
Custom	1 car	$12,500
	2 car	$19,700
	3 car	$26,600
Luxury	1 car	$14,700
	2 car	$23,300
	3 car	$31,700

Table 3.8 Weights (percent) for Means Construction/Condition Models

Income	Weights (w) for:			
	c_{Lg}	c_{Cg}	c_{Aa}	c_{Ep}
$I_k < 0.5$	-	-	70	30
$0.5 \leq I_k < 0.85$	-	-	100	-
$0.85 \leq I_k < 1.25$	-	-	100	-
$1.25 \leq I_k < 2.0$	-	60	40	-
$I_k \geq 2.0$	40	60	-	-

3.2.1.6. Contents Replacement Cost

Contents replacement value is estimated as a percent of structure replacement value. The NIBS Flood Module will utilize the same contents to structure value ratios as are employed in the NIBS Earthquake Module (Table 15.5 in the Hazus 1999 Technical Manual), provided in Table 3.10.

Table 3.10 Default Hazus Contents Value Percent of Structure Value

No.	Label	Occupancy Class	Contents Value (%)
		Residential	
1	RES1	Single Family Dwelling	50
2	RES2	Mobile Home	50
3	RES3	Multi Family Dwelling	50
4	RES4	Temporary Lodging	50
5	RES5	Institutional Dormitory	50
6	RES6	Nursing Home	50
		Commercial	
7	COM1	Retail Trade	100
8	COM2	Wholesale Trade	100
9	COM3	Personal and Repair Services	100
10	COM4	Professional/Technical/ Business Services	100
11	COM5	Banks	100
12	COM6	Hospital	150
13	COM7	Medical Office/Clinic	150
14	COM8	Entertainment & Recreation	100
15	COM9	Theaters	100
16	COM10	Parking	50
		Industrial	
17	IND1	Heavy	150
18	IND2	Light	150
19	IND3	Food/Drugs/Chemicals	150
20	IND4	Metals/Minerals Processing	150

No.	Label	Occupancy Class	Contents Value (%)
21	IND5	High Technology	150
22	IND6	Construction	100
		Agriculture	
23	AGR1	Agriculture	100
		Religion/Non/Profit	
24	REL1	Church/Membership Organization	100
		Government	
25	GOV1	General Services	100
26	GOV2	Emergency Response	150
		Education	
27	EDU1	Schools/Libraries	100
28	EDU2	Colleges/Universities	150

3.2.2. Essential Facilities

Essential facilities are those facilities that provide services to the community and should be functional after an earthquake. Essential facilities include hospitals, police stations, fire stations and schools. The damage state probabilities for essential facilities are determined on a site-specific basis (i.e., the ground motion parameters are computed at the location of the facility). The purpose of the essential facility module is to determine the expected loss of functionality for these critical facilities. Economic losses associated with these facilities are computed as part of the analysis of the general building stock (general building stock occupancy classes 12, 26, 27 and 28). The data required for the analysis include mapping of essential facility's occupancy classes to model building types or a combination of essential facilities building type, design level and construction quality factor. In addition, the number of beds for each hospital and the number of fire trucks at each fire station are required. The fire truck information is used as input for the fire following earthquake analysis (Chapter 10).

3.2.2.1. Classification

The essential facilities are also classified based on the building structure type and occupancy class. The building structure types of essential facilities are the same as those for the general building stock presented in Table 3.1. The occupancy classification is broken into general occupancy and specific occupancy classes. For the methodology, the general occupancy classification system consists of three groups (medical care, emergency response, and schools). Specific occupancy consists of nine classes. The occupancy classes are given in Table 3.11, where the general occupancy classes are identified in boldface. Relationships between specific and general occupancy classes are in a form shown in Table 3B.1 of Appendix 3B.

Table 3.11: Essential Facilities Classification

Label	Occupancy Class	Description
	Medical Care Facilities	
EFHS	Small Hospital	Hospital with less than 50 Beds
EFHM	Medium Hospital	Hospital with beds between 50 & 150
EFHL	Large Hospital	Hospital with greater than 150 Beds
EFMC	Medical Clinics	Clinics, Labs, Blood Banks
	Emergency Response	
EFFS	Fire Station	
EFPS	Police Station	
EFEO	Emergency Operation Centers	
	Schools	
EFS1	Grade Schools	Primary/ High Schools
EFS2	Colleges/Universities	

3.2.2.2. Occupancy to Model Building Type Relationship

Default mapping of essential facility occupancy classes to model building types is provided in Tables 3B.2 through 3B.16 of Appendix 3B. For the regional designation of a particular state, refer to Table 3C.1 in Appendix C. The default mapping of specific occupancy to model building type mapping is based on general building stock occupancy classes 12, 26, 27 and 28.

3.2.3. High Potential Loss Facilities

High potential loss facilities are facilities that are likely to cause heavy earthquake losses if damaged. For this methodology, high potential loss (HPL) facilities include nuclear power plants, dams, and some military installations. The inventory data required for HPL facilities include the geographical location (latitude and longitude) of the facility. Damage and loss estimation calculation for high potential loss facilities are not performed as part of the methodology.

3.2.3.1. Classification

Three types of HPL facilities are identified in the methodology (dams, nuclear power facilities and military installations) are shown in Table 3.12. The dam classification is based on the National Inventory of Dams (NATDAM) database (FEMA, 1993).

Table 3.12: High Potential Loss Facilities Classification

Label	Description
	Dams
HPDE	Earth
HPDR	Rock fill
HPDG	Gravity
HPDB	Buttress
HPDA	Arch
HPDU	Multi-Arch
HPDC	Concrete
HPDM	Masonry
HPDS	Stone
HPDT	Timber Crib
HPDZ	Miscellaneous
	Nuclear Power Facilities
HPNP	Nuclear Power Facilities
	Military Installations
HPMI	Military Installations

3.3. Direct Damage Data - Transportation Systems

The inventory classification scheme for lifeline systems separates components that make up the system into a set of pre-defined classes. The classification system used in this methodology was developed to provide an ability to differentiate between varying lifeline system components with substantially different damage and loss characteristics. Transportation systems addressed in the methodology include highways, railways, light rail, bus, ports, ferries and airports. The classification of each of these transportation systems is discussed in detail in the following sections. The inventory data required for the analysis of each system is also identified in the following sections.

For some transportation facilities, classification of the facility is based on whether the equipment is anchored or not. Anchored equipment in general refers to equipment designed with special seismic tie-downs or tiebacks, while unanchored equipment refers to equipment designed with no special considerations other than the manufacturer's normal requirements. While some vibrating components, such as pumps, are bolted down regardless of concern for earthquakes, as used here "anchored" means all components have been engineered to meet seismic criteria which may include bracing (e.g., pipe or stack bracing) or flexibility requirements (e.g., flexible connections across separation joints) as well as anchorage.

3.3.1. Highway Systems

A highway transportation system consists of roadways, bridges and tunnels. The inventory data required for analysis include the geographical location, classification, and replacement cost of the system components. The analysis also requires the length of each highway segment.

3.3.1.1. Classification

The classes of highway system components are presented in Table 3.13. For more details on how to classify these components, refer to section 7.1.5 of Chapter 7.

Table 3.13: Highway System Classification

Label	Description
	Hignhway Roads
HRD1	Major Roads
HRD2	Urban Roads
	Highnway Bridges
HWB1	Major Bridge - Length > 150m (Conventional Design)
HWB2	Major Bridge - Length > 150m (Seismic Design)
HWB3	Single Span – (Not HWB1 or HWB2) (Conventional Design)
HWB4	Single Span – (Not HWB1 or HWB2) (Seismic Design)
HWB5	Concrete, Multi-Column Bent, Simple Support (Conventional Design), Non-California (Non-CA)
HWB6	Concrete, Multi-Column Bent, Simple Support (Conventional Design), California (CA)
HWB7	Concrete, Multi-Column Bent, Simple Support (Seismic Design)
HWB8	Continuous Concrete, Single Column, Box Girder (Conventional Design)
HWB9	Continuous Concrete, Single Column, Box Girder (Seismic Design)
HWB10	Continuous Concrete, (Not HWB8 or HWB9) (Conventional Design)
HWB11	Continuous Concrete, (Not HWB8 or HWB9) (Seismic Design)
HWB12	Steel, Multi-Column Bent, Simple Support (Conventional Design), Non-California (Non-CA)
HWB13	Steel, Multi-Column Bent, Simple Support (Conventional Design), California (CA)
HWB14	Steel, Multi-Column Bent, Simple Support (Seismic Design)
HWB15	Continuous Steel (Conventional Design)
HWB16	Continuous Steel (Seismic Design)
HWB17	PS Concrete Multi-Column Bent, Simple Support - (Conventional Design), Non-California
HWB18	PS Concrete, Multi-Column Bent, Simple Support (Conventional Design), California (CA)
HWB19	PS Concrete, Multi-Column Bent, Simple Support (Seismic Design)
HWB20	PS Concrete, Single Column, Box Girder (Conventional Design)
HWB21	PS Concrete, Single Column, Box Girder (Seismic Design)
HWB22	Continuous Concrete, (Not HWB20/HWB21) (Conventional Design)
HWB23	Continuous Concrete, (Not HWB20/HWB21) (Seismic Design)
HWB24	Same definition as HWB12 except that the bridge length is less than 20 meters
HWB25	Same definition as HWB13 except that the bridge length is less than 20 meters
HWB26	Same definition as HWB15 except that the bridge length is less than 20 meters and Non-CA
HWB27	Same definition as HWB15 except that the bridge length is less than 20 meters and in CA
HWB28	All other bridges that are not classified (including wooden bridges)
	Highwnay Tunnels
HTU1	Highway Bored/Drilled Tunnel
HTU2	Highway Cut and Cover Tunnel

3.3.2. Railways

A railway transportation system consists of tracks, bridges, tunnels, stations, and fuel, dispatch and maintenance facilities. The inventory data required for analysis include the geographical location, classification and replacement cost of the facilities, bridges, tunnels, and track segments. The analysis also requires the length of the railway segments.

3.3.2.1. Classification

The various classes of railway system components are presented in Table 3.14. For more details on how to classify these components refer to section 7.2 of Chapter 7.

Table 3.14: Railway System Classification

Label	Description
	Railway Tracks
RTR1	Railway Tracks
	Railway Bridges
RLB1	Steel, Multi-Column Bent, Simple Support (Conventional Design), Non-California (Non-CA)
RLB2	Steel, Multi-Column Bent, Simple Support (Conventional Design), California (CA)
RLB3	Steel, Multi-Column Bent, Simple Support (Seismic Design)
RLB4	Continuous Steel (Conventional Design)
RLB5	Continuous Steel (Seismic Design)
RLB6	Same definition as HWB1 except that the bridge length is less than 20 meters
RLB7	Same definition as HWB2 except that the bridge length is less than 20 meters
RLB8	Same definition as HWB4 except that the bridge length is less than 20 meters and Non-CA
RLB9	Same definition as HWB5 except that the bridge length is less than 20 meters and in CA
RLB10	All other bridges that are not classified
RST	**Railway Urban Station** Rail Urban Station (with all building type options enabled)
	Railway Tunnels
RTU1	Rail Bored/Drilled Tunnel
RTU2	Rail Cut and Cover Tunnel
	Railway Fuel Facility
RFF	Rail Fuel Facility (different combinations for with or without anchored components and/or with or without backup power)
	Railway Dispatch Facility
RDF	Rail Dispatch Facility (different combinations for with or without anchored components and/or with or without backup power)
	Railway Maintenance Facility
RMF	Rail Maintenance Facility (with all building type options enabled)

3.3.3. Light Rail

Like railways, light rail systems are composed of tracks, bridges, tunnels, and facilities. The major difference between the two is with regards to power supply, where light rail systems operate with DC power substations. The inventory data required for analysis include the classification, geographical location, and replacement cost of facilities, bridges, tunnels, and tracks. In addition, the analysis requires the track length.

3.3.3.1. Classification

Table 3.15 describes the various classes of light rail system components. For more details on how to classify these components refer to section 7.3 of Chapter 7.

Table 3.15: Light Rail System Classification

Label	Description
	Light Rail Tracks
LTR1	Light Rail Track
	Light Rail Bridges
LRB1	Steel, Multi-Column Bent, Simple Support (Conventional Design), Non-California (Non-CA)
LRB2	Steel, Multi-Column Bent, Simple Support (Conventional Design), California (CA)
LRB3	Steel, Multi-Column Bent, Simple Support (Seismic Design)
LRB4	Continuous Steel (Conventional Design)
LRB5	Continuous Steel (Seismic Design)
LRB6	Same definition as HWB1 except that the bridge length is less than 20 meters
LRB7	Same definition as HWB2 except that the bridge length is less than 20 meters
LRB8	Same definition as HWB4 except that the bridge length is less than 20 meters and Non-CA
LRB9	Same definition as HWB5 except that the bridge length is less than 20 meters and in CA
LRB10	All other bridges that are not classified
	Light Rail Tunnels
LTU1	Light Rail Bored/Drilled Tunnel
LTU2	Light Rail Cut and Cover Tunnel
	DC Substation
LDC1	Light Rail DC Substation w/ Anchored Sub-Components
LDC2	Light Rail DC Substation w/ Unanchored Sub-Components
	Dispatch Facility
LDF	Light Rail Dispatch Facility (different combinations for with or without anchored components and/or with or without backup power)
	Maintenance Facility
LMF	Maintenance Facility (with all building type options enabled)

3.3.4. Bus System

A bus transportation system consists of urban stations, fuel facilities, dispatch facilities and maintenance facilities. The inventory data required for bus systems analysis include the geographical location, classification, and replacement cost of bus system facilities.

3.3.4.1. Classification

Table 3.16 describes the various classes of bus system components. For more details on how to classify these components refer to section 7.4 of Chapter 7.

Table 3.16: Bus System Classification

Label	Description
	Bus Urban Station
BPT	Bus Urban Station (with all building type options enabled)
	Bus Fuel Facility
BFF	Bus Fuel Facility (different combinations for with or without anchored components and/or with or without backup power)
	Bus Dispatch Facility
BDF	Bus Dispatch Facility (different combinations for with or without anchored components and/or with or without backup power)
	Bus Maintenance Facility
BMF	Bus Maintenance Facilities (with all building type options enabled)

3.3.4.2.Ports and Harbors

Port and harbor transportation systems consist of waterfront structures, cranes/cargo handling equipment, warehouses and fuel facilities. The inventory data required for ports and harbors analysis include the geographical location, classification and replacement cost of the port and harbor system facilities.

3.3.4.3. Classification

Table 3.17 describes the various classes of port and harbor transportation system components. For more details on how to classify these components refer to section 7.5 of Chapter 7.

Table 3.17: Port and Harbor System Classification

Label	Description
	Waterfront Structures
PWS	Waterfront Structures
	Cranes/Cargo Handling Equipment
PEQ1	Stationary Port Handling Equipment
PEQ2	Rail Mounted Port Handling Equipment
	Warehouses
PWH	Port Warehouses (with all building type options enabled)
	Fuel Facility
PFF	Port Fuel Facility Facility (different combinations for with or without anchored components and/or with or without backup power)

3.3.4.4.Ferry

A ferry transportation system consists of waterfront structures, passenger terminals, fuel facilities, dispatch facilities and maintenance facilities. The inventory data required for ferry systems analysis include the geographical location, classification and replacement cost of ferry system facilities.

3.3.4.5. Classification

Table 3.18 describes the various classes of ferry transportation system components. For more details on how to classify these components refer to section 7.6 of Chapter 7.

Table 3.18: Ferry System Classification

Label	Description
	Water Front Structures
FWS	Ferry Waterfront Structures
	Ferry Passenger Terminals
FPT	Passenger Terminals (with all building type options enabled)
	Ferry Fuel Facility
FFF	Ferry Fuel Facility (different combinations for with or without anchored components and/or with or without backup power)
	Ferry Dispatch Facility
FDF	Ferry Dispatch Facility (different combinations for with or without anchored components and/or with or without backup power)
	Ferry Maintenance Facility
FMF	Piers and Dock Facilities (with all building type options enabled)

3.3.5. Airports

An airport transportation system consists of control towers, runways, terminal buildings, parking structures, fuel facilities, and maintenance and hangar facilities. The inventory data required for airports analysis include the geographical location, classification and replacement cost of airport facilities.

3.3.5.1. Classification

Table 3.19 describes the various classes of airport system components. For more details on how to classify these components refer to section 7.7 of Chapter 7.

Table 3.19: Airport System Classification

Label	Description
	Airport Control Towers
ACT	Airport Control Tower (with all building type options enabled)
	Airport Terminal Buildings
ATB	Airport Terminal Building (with all building type options enabled)
	Airport Parking Structures
APS	Airport Parking Structure (with all building type options enabled)
	Fuel Facilities
AFF	Airport Fuel Facility (different combinations for with or without anchored components and/or with or without backup power)
	Airport Maintenance & Hangar Facility
AMF	Airport Maintenance & Hangar Facility (with all building type options enabled)
ARW	Airport Runway
	Airport Facilities - Others
AFO	Gliderport, Seaport, Stolport, Ultralight or Baloonport Facilities
AFH	Heliport Facilities

3.4. Direct Damage Data - Lifeline Utility Systems

Lifeline utility systems include potable water, waste water, oil, natural gas, electric power and communication systems. This section describes the classification of lifeline utility system and their components, and data required to provide damage and loss estimates.

3.4.1. Potable Water System

A potable water system consists of pipelines, water treatment plants, wells, storage tanks and pumping stations. The inventory data required for potable water systems analysis include the geographical location and classification of system components. The analysis also requires the replacement cost for facilities and the repair cost for pipelines.

3.4.1.1. Classification

Table 3.20 describes the various classes of potable water system components. For more details on how to classify these components refer to section 8.1 of Chapter 8.

Table 3.20: Potable Water System Classification

Label	Description
	Pipelines
PWP1	Brittle Pipe
PWP2	Ductile Pipe
	Pumping Plants
PPPL	Large Pumping Plant (> 50 MGD) [different combinations for with or without anchored components]
PPPM	Medium Pumping Plant (10 to 50 MGD) [different combinations for with or without anchored components]
PPPS	Small Pumping Plant (< 10 MGD) [different combinations for with or without anchored components]
	Wells
PWE	Wells
	Water Storage Tanks (Typically, 0.5 MGD to 2 MGD)
PSTAS	Above Ground Steel Tank
PSTBC	Buried Concrete Tank
PSTGC	On Ground Concrete Tank
PSTGS	On Ground Steel Tank
PSTGW	On Ground Wood Tank
	Water Treatment Plants
PWTL	Large WTP (> 200 MGD) [different combinations for with or without anchored components]
PWTM	Medium WTP (50-200 MGD) [different combinations for with or without anchored components]
PWTS	Small WTP (< 50 MGD) [different combinations for with or without anchored components]

3.4.2. Waste Water

A waste water system consists of pipelines, waste water treatment plants and lift stations. The inventory data required for waste water systems analysis include the geographical location and classification of system components. The analysis also requires the replacement cost for facilities and the repair cost for pipelines.

3.4.2.1. Classification

Table 3.21 describes the various classes of waste water system components. For more details on how to classify these components refer to section 8.2 of Chapter 8.

Table 3.21: Waste Water System Classification

Label	Description
	Buried Pipelines
WWP1	Brittle Pipe
WWP2	Ductile Pipe
	Waste Water Treatment Plants
WWTL	Large WWTP (> 200 MGD) [different combinations for with or without anchored components]
WWTM	Medium WWTP (50-200 MGD) [different combinations for with or without anchored components]
WWTS	Small WWTP (< 50 MGD) [different combinations for with or without anchored components]
	Lift Stations
WLSL	Large Lift Stations (> 50 MGD) [different combinations for with or without anchored components]
WLSM	Medium Lift Stations (10 MGD - 50 MGD) [different combinations for with or without anchored components]
WLSS	Small Lift Stations (< 10 MGD) [different combinations for with or without anchored components]

3.4.3. Oil Systems

An oil system consists of pipelines, refineries, pumping plants and tank farms. The inventory data required for oil systems analysis include the geographical location and classification of system components. The analysis also requires the replacement cost for facilities and the repair cost for pipelines.

3.4.3.1. Classification

Table 3.22 describes the various classes of oil system components. For more details on how to classify these components refer to section 8.3 of Chapter 8.

Table 3.22: Oil System Classification

Label	Description
	Pipelines
OIP1	Welded Steel Pipe with Gas Welded Joints
OIP2	Welded Steel Pipe with Arc Welded Joints
	Refineries
ORFL	Large Refinery (> 500,000 lb./day) [different combinations for with or without anchored components]
ORFM	Medium Refinery (100,000 - 500,000 lb./ day) [different combinations for with or without anchored components]
ORFS	Small Refinery (< 100,000 lb./day) [different combinations for with or without anchored components]
	Pumping Plants
OPP	Pumping Plant [different combinations for with or without anchored components]
	Tank Farms
OTF	Tank Farms with Anchored Tanks [different combinations for with or without anchored components]

3.4.4. Natural Gas Systems

A natural gas system consists of pipelines and compressor stations. The inventory data required for natural gas systems analysis include the geographical location and classification of system components. The analysis also requires the replacement cost for facilities and the repair cost for pipelines.

3.4.4.1. Classification

Table 3.23 describes the various classes of natural gas system components. For more details on how to classify these components refer to section 8.4 of Chapter 8.

Table 3.23: Natural Gas System Classification

Label	Description
	Buried Pipelines
NGP1	Welded Steel Pipe with Gas Welded Joints
NGP2	Welded Steel Pipe with Arc Welded Joints
	Compressor Stations
NGC	Compressor Stations [different combinations for with or without anchored components]

3.4.5. Electric Power

An electric power system consists of substations, distribution circuits, generation plants and transmission towers. The inventory data required for electric power systems analysis include the geographical location, classification and replacement cost of the facilities.

3.4.5.1. Classification

Table 3.24 describes the various classes of electric power system components. For more details on how to classify these components refer to section 8.5 of Chapter 8.

Table 3.24: Electric Power System Classification

Label	Description
	Transmission Substations
ESSL	Low Voltage (115 KV) Substation [different combinations for with or without anchored components]
ESSM	Medium Voltage (230 KV) Substation [different combinations for with or without anchored components]
ESSH	High Voltage (500 KV) Substation [different combinations for with or without anchored components]
	Distribution Circuits
EDC	Distribution Circuits (either Seismically Designed Components or Standard Components)
	Generation Plants
EPPL	Large Power Plants (> 500 MW) [different combinations for with or without anchored components]
EPPM	Medium Power Plants (100 - 500 MW) [different combinations for with or without anchored components]
EPPS	Small Power Plants (< 100 MW) [different combinations for with or without anchored components]

3.4.6. Communication

In the loss estimation methodology, a communication system consists of telephone central offices. The inventory data required for communication systems analysis include the geographical location and the classification. The analysis also requires the replacement cost of the facilities.

3.4.6.1. Classification

Table 3.25 describes the various classes of central offices. For more details on how to classify these components refer to section 8.6 of Chapter 8.

Table 3.25: Communication Classification

Label	Description
	Central Offices
CCO	Central Offices (different combinations for with or without anchored components and/or with or without backup power)
	Stations or Transmitters
CBR	AM or FM radio stations or transmitters
CBT	TV stations or transmitters
CBW	Weather stations or transmitters
CBO	Other stations or transmitters

3.5. Hazardous Materials Facilities

Hazardous material facilities contain substances that can pose significant hazards because of their toxicity, radioactivity, flammability, explosiveness or reactivity. Significant casualties or property damage could occur form a small number or even a single hazardous materials release induced by an earthquake, and the consequence of an earthquake-caused release can vary greatly according to the type and quantity of substance released, meteorological conditions and timeliness and effectiveness of emergency response. Similarly to the case of critical faculties with a potential for high loss, such as large dams, the methodology does not attempt to estimate losses caused by earthquake which caused hazardous materials releases. Thus, the hazardous materials module of **Hazus** is limited to inventory data concerning the location and nature of hazardous materials located at various sites. Section 11.1.2 describes the scheme used to define the degree of danger of hazardous materials.

3.6. Direct Economic and Social Loss

In this section, information related to inventory data required to determine direct economic and social loss is presented. The two main databases used to determine direct economic and social loss are demographic and building square footage databases.

3.6.1. Demographics Data

The census data are used to estimate direct social loss due to displaced households, casualties due to earthquakes, and the estimation quality of building space (square footage) for certain occupancy classes. The Census Bureau collects and publishes statistics about the people of the United States based on the constitutionally required census every 10 years, which is taken in the years ending in "0" (e.g., 1990). The Bureau's population census data describes the characteristics of the population including age, income, housing and ethnic origin.

The census data were processed for all of the census tracts in the United States, and 29 fields of direct importance to the methodology were extracted and stored. These fields are shown in Table 3.26 and are supplied as default information with the methodology. The population information is aggregated to a census tract level. Census tracts are divisions of land that are designed to contain 2500-8000 inhabitants with relatively homogeneous population characteristics, economic status and living conditions. Census tract divisions and boundaries change only once every ten years. Census tract boundaries never cross county boundaries, and all the area within a county is contained within one or more census tracts. This characteristic allows for a unique division of land from country to state to county to census tract. Each Census tract is identified by a unique 11 digit number. The first two digits represent the tract's state, the next three digits represent the tract's county, while the last 6 digits identify the tract within the county. For example, a census tract numbered 10050505800 would be located in Delaware (10) in Sussex County (050).

Table 3.26: Demographics Data Fields and Usage

	Module Usage			
Description of Field	**Shelter**	**Casualty**	**Occupancy Class**	**Lifelines**
Total Population in Census Tract	*			*
Total Household in Census Tract	*			*
Total Number of People in General Quarter	*			
Total Number of People < 16 years old	*			
Total Number of People 16-65 years old	*			
Total Number of People > 65 years old	*			
Total Number of People - White	*			
Total Number of People - Black	*			
Total Number of People - Native American	*			
Total Number of People - Asian	*			
Total Number of People - Hispanic	*			
Total # of Households with Income < $10,000	*			
Total # of Households with Income $10 - $20K	*			
Total # of Households with Income $20 - $30K	*			
Total # of Households with Income $30 - $40K	*			
Total # of Households with Income $40 - $50K	*			
Total # of Households with Income $50 - $60K	*			
Total # of Households with Income $60 - $75K	*			
Total # of Households with Income $75 - $100K	*			
Total # of Households with Income > $100k	*			
Total in Residential Property during Day		*		
Total in Residential Property at Night		*		
Hotel Occupants		*		
Vistor Population		*		
Total Working Population in Commercial Industry		*		
Total Working Population in Industrial Industry		*		
Total Commuting at 5 PM		*		
Total Number of Students in Grade School		*		
Total Number of Students in College/University		*		
Total Owner Occupied - Single Household Units	*		*	
Total Owner Occupied - Multi-Household Units	*		*	
Total Owner Occupied - Multi-Household Structure	*		*	
Total Owner Occupied - Mobile Homes	*		*	
Total Renter Occupied - Single Household Units	*		*	
Total Renter Occupied - Multi-Household Units	*		*	
Total Renter Occupied - Multi-Household Structure	*		*	
Total Renter Occupied - Mobile Homes	*		*	
Total Vacant - Single Household Units			*	
Total Vacant - Multi-Household Units			*	
Total Vacant - Multi-Household Structure			*	
Total Vacant - Mobile Homes			*	
Structure Age <40 years			*	
Structure Age >40 years			*	

3.6.2. Default Occupancy Class Square Foot Inventory

The default square footage estimates for occupancy classes RES1, 2,3,5, are based on census data on the number of dwelling units or the number of people for that occupancy class. Table 3.27 provides the conversion factors for these occupancy classes. These conversion factors are obtained from expert opinion and modifications to ATC-13 values. The conversion factors were also calibrated against tax assessors data for region-specific counties. The square foot estimates are calculated using the following expression:

$$SFI = UD * CF \tag{3-4}$$

where,

SFI = building square footage for an occupancy class
UD = unit of data for that occupancy class
CF = conversion factor for that occupancy class (Table 3.27)

The building square footage estimates for the remaining occupancy classes were obtained using a building square footage inventory database purchased from the Dun and Bradstreet Company (D&B). The square footage information was classified based on Standard Industrial Code (SIC) and provided at a census tract resolution. The SIC codes were mapped to NIBS occupancy classes using the mapping scheme provided in Table 3.27. There is no default information for occupancy class COM10.

3.7. Indirect Economic Data

The indirect economic data refers to the post-earthquake change in the demand and supply of products, change in employment and change in tax revenues. The user can specify the levels of potential increase in imports and exports, supply and product inventories and unemployment rates.

Table 3.27: Mapping of Standard Industrial Codes, Conversion Factors to Estimate Occupancy Square Footage and Square Footage Per Occupancy Class

		Source of Data		
Label	**Occupancy Class**	**Census**		**Dun and Bradstreet**
		Unit of Data	**Conversion Factor**	**SIC Code**
	Residential			
RES1	Single Family Dwelling	# of Units	variable	
RES2	Mobile Home	# of Units	1000 sq. t./unit	
RES3	Multi Family Dwelling	# of Units	1000 sq. t./unit	
RES4	Temporary Lodging			70
RES5	Institutional Dormitory	# in Group Quarters	700 sq. ft./person	
RES6	Nursing Home			8051, 8052, 8059
	Commercial			
COM1	Retail Trade			52, 53, 54, 55, 56, 57, 59
COM2	Wholesale Trade			42, 50, 51
COM3	Personal/Repair Services			72,75,76,83,88
COM4	Prof./Technical Services			40, 41, 44, 45, 46, 47, 49, 61, 62, 63, 64, 65, 67, 73, 78 (except 7832), 81, 87, 89
COM5	Banks			60
COM6	Hospital			8062, 8063, 8069
COM7	Medical Office/Clinic			80 (except 8051, 8052, 8059, 8062, 8063, 8069)
COM8	Entertainment & Rec.			48, 58, 79, (except 7911), 84
COM9	Theaters			7832, 7911
COM10	Parking			
	Industrial			
IND1	Heavy			22, 24, 26, 32, 34, 35 (except 3571, 3572), 37
IND2	Light			23, 25, 27, 30, 31, 36 (except 3671, 3672, 3674), 38, 39
IND3	Food/Drugs/Chemicals			20, 21, 28, 29
IND4	Metals/Minerals Processing.			10, 12, 13, 14, 33
IND5	High Technology			3571, 3572, 3671, 3672, 3674
IND6	Construction			15, 16, 17
	Agriculture			
AGR1	Agriculture			01, 02, 07, 08, 09
	Religion/Non/Profit			
REL1	Church/ N.P. Offices			86
	Government			
GOV1	General Services			43, 91, 92 (except 9221, 9224), 93, 94, 95, 96, 97
GOV2	Emergency Response			9221, 9224
	Education			
EDU1	Schools			82 (except 8221, 8222)
EDU2	Colleges/Universities			8221, 8222

3.8. References

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U.S. Bureau of the Census, May 1991. *Standard Tape File 1 (STF-1A)***.**

U.S. Bureau of the Census, May 1992. *Standard Tape File 3 (STF-3)***.**

APPENDIX 3A
General Building Stock

Table 3A.1: Distribution Percentage of Floor Area for Specific Occupancy Classes within each General Occupancy Class♦

Specific Occupancy Class			General Occupancy Class						
			RES	COM	IND	AGR	REL	GOV	EDU
No.	Label	Occupancy Class	1	2	3	4	5	6	7
1	RES1	Single Family Dwelling	♦						
2	RES2	Mobile Home	♦						
3	RES3	Multi Family Dwelling	♦						
4	RES4	Temporary Lodging	♦						
5	RES5	Institutional Dormitory	♦						
6	RES6	Nursing Home	♦						
7	COM1	Retail Trade		♦					
8	COM2	Wholesale Trade		♦					
9	COM3	Personal and Repair Services		♦					
10	COM4	Professional/Technical		♦					
11	COM5	Banks		♦					
12	COM6	Hospital		♦					
13	COM7	Medical Office/Clinic		♦					
14	COM8	Entertainment & Recreation		♦					
15	COM9	Theaters		♦					
16	COM10	Parking		♦					
17	IND1	Heavy			♦				
18	IND2	Light			♦				
19	IND3	Food/Drugs/Chemicals			♦				
20	IND4	Metals/Minerals Processing			♦				
21	IND5	High Technology			♦				
22	IND6	Construction			♦				
23	AGR1	Agriculture				100			
24	REL1	Church					100		
25	GOV1	General Services						♦	
26	GOV2	Emergency Response						♦	
27	EDU1	Schools							♦
28	EDU2	Colleges/Universities							♦

♦ The relative distribution varies by census tract and is computed directly from the specific occupancy class square footage inventory. For Agriculture (AGR) and Religion (REL) there is only one specific occupancy class, therefore the distribution is always 100%.

Table 3A.2: Distribution Percentage of Floor Area for Model Building Types within Each Building Occupancy Class, Low Rise, Pre-1950, West Coast* (after ATC-13, 1985)

No.	Specific Occup. Class	Model Building Type															
		1	2	3	6	9	10	13	16	19	22	25	26	29	31	34	36
		W1	W2	S1L	S2L	S3	S4L	S5L	C1L	C2L	C3L	PC1	PC2L	RM1L	RM2L	URML	MH
1	RES1	For State-Specific "Res1" Distribution, Refer to Table 3A.17															
2	RES2																100
3	RES3	73		1	1	1		6		3	3			1		9	2
4	RES4	34		2	1	2	1	19		16	3			4		18	
5	RES5	20		5	1		1			28	18			6		21	
6	RES6	45				10		5		10				20		10	
7	COM1		22	2		6	3	20		17	1			6		23	
8	COM2		8	3		4	2	41		18	1	3		5	2	13	
9	COM3		28	1	1	3		18		7		1		8		33	
10	COM4		27	2	1	3		19		15				7		26	
11	COM5		27	2	1	3		19		15				7		26	
12	COM6		8	5	2	11		11		27	2	1		27		6	
13	COM7		25	5	2	10		10		15	2	1		20		10	
14	COM8		8	12	1	2	3	16		27	4			5	1	21	
15	COM9		5	20	7			15		20	3			10		20	
16	COM10				8		8	18		43	7		1	6	3	6	
17	IND1		3	29	13	2	2	15		14	7	1		4	2	8	
18	IND2		4	14	8	22	1	18		16	1	1		2		13	
19	IND3		1	18	8	3	3	20		22		2		3		20	
20	IND4		2	24	12	7	2	13		16		2		2	6	14	
21	IND5			21	5	5		3		35	2	10	2	15		2	
22	IND6		32	3	2	10		18		8	7					13	7
23	AGR1	56		3	2	14		2		9					1	13	
24	REL1	22		8		2		21		15	5			8		19	
25	GOV1		9	8	1	3	4	12		42	4			6		11	
26	GOV2	45					2			37				3		13	
27	EDU1	11		6		3	3	21		21	4			9		22	
28	EDU2	2		5	10		5	15		20				20	5	18	

* Refer to Table 3C.1 for states' classifications.

Table 3A.3: Distribution Percentage of Floor Area for Model Building Types within Each Building Occupancy Class, Low Rise, 1950-1970 , West Coast* (after ATC-13, 1985)

No.	Specific Occup. Class	Model Building Type															
		1	**2**	**3**	**6**	**9**	**10**	**13**	**16**	**19**	**22**	**25**	**26**	**29**	**31**	**34**	**36**
		W1	W2	S1L	S2L	S3	S4L	S5L	C1L	C2L	C3L	PC1	PC2L	RM1L	RM2L	URML	MH
1	RES1	For State-Specific "Res1" Distribution, Refer to Table 3A.18															
2	RES2																100
3	RES3	72		1	2	2		1		6	2			8		3	3
4	RES4	55		1	2	2	2	3		11	2			18	1	3	
5	RES5	39		3	3		1	8		16	6			18	1	5	
6	RES6	70				3	1	1		5				20			
7	COM1		34	3	1	3	2	4		13	5	10	1	18	2	4	
8	COM2		12	4	5	5	3	3		18		22	1	19	4	4	
9	COM3		12	3	5	5	2	3		23	4	12	1	22	4	4	
10	COM4		34	3	3	1	2	3		17	5	3		23	4	2	
11	COM5		34	3	3	1	2	3		17	5	3		23	4	2	
12	COM6		32	5	2	4	3			16	6			28	4		
13	COM7		46	13	1	3	3			9				20		5	
14	COM8		13	17	12	3	3			13	6			30	3		
15	COM9		10	10	30			5		10		5		30			
16	COM10			5	8		20			34			5	20	6	2	
17	IND1		10	25	30	3			7	14				9	2		
18	IND2		8	5	14	17	4			10	5	22	3	12			
19	IND3			14	16	6	1		5	17		28	1	10	2		
20	IND4			18	25	9			11	10		7		15	3		2
21	IND5			4	9	3	2		4	20		35	3	15	4		1
22	IND6		30		1	15				7		4		20	3		20
23	AGR1	51		4	8	12				2		10		11	2		
24	REL1	20		4	1	3	3			24		4		37	4		
25	GOV1		21	6	3	2	2			26	5	4	2	27	2		
26	GOV2	50								13		7		20	10		
27	EDU1	25		3	4	5	4			20		4	2	29	4		
28	EDU2	5		2	12		5			20				50	6		

* Refer to Table 3C.1 for states' classifications.

Table 3A.4: Distribution Percentage of Floor Area for Model Building Types within Each Building Occupancy Class, Low Rise, Post-1970, West Coast* (after ATC-13, 1985)

No.	Specific Occup. Class	Model Building Type															
		1	2	3	6	9	10	13	16	19	22	25	26	29	31	34	36
		W1	W2	S1L	S2L	S3	S4L	S5L	C1L	C2L	C3L	PC1	PC2L	RM1L	RM2L	URML	MH
1	RES1	For State-Specific "Res1" Distribution, Refer to Table 3A.19															
2	RES2																100
3	RES3	73				2	3			6	1		1	9			5
4	RES4	53		3		2	3		4	13				20	2		
5	RES5	33		3	3		6		5	24				23	3		
6	RES6	70								5		5		20			
7	COM1		26	9	1	2	1		6	10	1	15	5	21	3		
8	COM2		8	4	1	3	4		2	12		41	3	19	3		
9	COM3		13	3	2	2	3		3	13		20	5	34	2		
10	COM4		35	3	2	1	3		4	15		8	3	24	2		
11	COM5		35	3	2	1	3		4	15		8	3	24	2		
12	COM6		31	6	1	1	7		4	13		7		28	2		
13	COM7		47	16			5		4	6		2		20			
14	COM8		4	23	8	1	3		2	15		4	1	32	7		
15	COM9		5	27	20					12		4		27	5		
16	COM10			8	8		6		3	49		3	13	7	3		
17	IND1		11	19	28	3	2		1	9		11	3	11	1		1
18	IND2		3	13	9	6	3			10		41	3	12			
19	IND3		2	15	10	5	3			12		28	7	18			
20	IND4		1	26	18	5	4		1	11	1	12	5	15	1		
21	IND5		1	12	8	2	3			10		38	7	17	1		1
22	IND6		30	4	6	11				8		16	6	14			5
23	AGR1	40		8	11	8				3		11	1	15	1		2
24	REL1	23		12	3	1	6			26		1	3	22	3		
25	GOV1		8	15	4	3	7		2	32			4	16	9		
26	GOV2	40		3	7		23			10			7	3	7		
27	EDU1	24		9	6	1	5		3	16	3	4	3	21	5		
28	EDU2	5		10	10		5			20		5		40	5		

* Refer to Table 3C.1 for states' classifications.

Table 3A.5: Distribution Percentage of Floor Area for Model Building Types within Each Building Occupancy Class, Mid Rise, Pre-1950, West Coast* (after ATC-13, 1985)

No.	Specific Occupancy Class	Model Building Type										
		4	7	11	14	17	20	23	27	30	32	35
		S1M	S2M	S4M	S5M	C1M	C2M	C3M	PC2M	RM1M	RM2M	URMM
3	RES3	15	4	5		1	19	25		8		23
4	RES4	18	4	12		1	20	20		8		17
5	RES5	16	1	5			40	20				18
6	RES6	20		5			35	20		10		10
7	COM1	8	6	3			21	34		11	1	16
8	COM2	8					27	53		5		7
9	COM3	18					22	42		5		13
10	COM4	25	7	10		2	22	16		9		9
11	COM5	25	7	10		2	22	16		9		9
12	COM6	18	4	6		1	35	19		8		9
13	COM7	20	5	5			30	20		10		10
14	COM8	25		20			40	5				10
15	COM9	30		10			40	10				10
16	COM10		10	5		2	55	18		3	2	5
17	IND1											
18	IND2			10			5	75				10
19	IND3	32	3	1		1	14	41		3		5
20	IND4	25	3	1			9	52				10
21	IND5	35	10				30	5		20		
22	IND6						20	80				
23	AGR1						25	75				
24	REL1						10	90				
25	GOV1	30	15	5		3	23	10		4		10
26	GOV2											
28	EDU2	10		20			60	3		5		2

* Refer to Table 3C.1 for states' classifications.

Table 3A.6: Distribution Percentage of Floor Area for Model Building Types within Each Building Occupancy Class, Mid Rise, 1950-1970, West Coast* (after ATC-13, 1985)

No.	Specific Occup. Class	Model Building Type										
		4	**7**	**11**	**14**	**17**	**20**	**23**	**27**	**30**	**32**	**35**
		S1M	S2M	S4M	S5M	C1M	C2M	C3M	PC2M	RM1M	RM2M	URMM
3	RES3	10	15	6		4	37		1	21	6	
4	RES4	9	24	9		5	34	1		14	4	
5	RES5	6	1	11		9	45			18	10	
6	RES6	15	10	15		5	25			25	5	
7	COM1	7	25	5		3	31			22	7	
8	COM2	21	3			2	34		1	34	5	
9	COM3	10	3				28			54	5	
10	COM4	17	18	9		9	18		2	23	4	
11	COM5	17	18	9		9	18		2	23	4	
12	COM6	14	10	14		5	23		3	23	8	
13	COM7	15	10	15		5	25			25	5	
14	COM8	5		28			52			10	5	
15	COM9	5		30			50			10	5	
16	COM10	5	8	8		7	39		8	18	7	
17	IND1		10	20			40			20	10	
18	IND2		15	10			50			20	5	
19	IND3	11	4	10		30	20		1	15	9	
20	IND4					100						
21	IND5	10	5	13			32			30	10	
22	IND6											
23	AGR1											
24	REL1						80			10	10	
25	GOV1	15	6	15		11	28		2	18	5	
26	GOV2	5	10	10		5	60				10	
28	EDU2	20		15		5	35			15	10	

***** Refer to Table 3C.1 for states' classifications.

Table 3A.7: Distribution Percentage of Floor Area for Model Building Types within Each Building Occupancy Class, Mid Rise, Post-1970, West Coast* (after ATC-13, 1985)

No.	Specific Occupancy Class	Model Building Type										
		4	7	11	14	17	20	23	27	30	32	35
		S1M	S2M	S4M	S5M	C1M	C2M	C3M	PC2M	RM1M	RM2M	URMM
3	RES3	9	23	8		10	28		7	12	3	
4	RES4	16	28	8		11	18		3	13	3	
5	RES5	9	10	11		16	34		4	11	5	
6	RES6	25	10	15		10	35			5		
7	COM1	34	9	3		12	17		5	15	5	
8	COM2	20	17			15	10		8	15	15	
9	COM3	11	17	3		10	17		12	17	13	
10	COM4	37	10	12		9	15		3	9	5	
11	COM5	37	10	12		9	15		3	9	5	
12	COM6	25	9	15		10	33		1	6	1	
13	COM7	25	10	15		10	35			5		
14	COM8		10			90						
15	COM9		10			90						
16	COM10	4	8	3		4	66		8	6	1	
17	IND1											
18	IND2											
19	IND3	62	5	1		23	4		1	3	1	
20	IND4	100										
21	IND5	18	14	3		34	13		5	10	3	
22	IND6											
23	AGR1											
24	REL1		5			90					5	
25	GOV1	25	11	15		22	12		4	9	2	
26	GOV2	25	20	35			20					
28	EDU2	20	5	10		25	25			10	5	

* Refer to Table 3C.1 for states' classifications.

Table 3A.8: Distribution Percentage of Floor Area for Model Building Types within Each Building Occupancy Class, High Rise, Pre-1950, West Coast* (after ATC-13, 1985)

No.	Specific Occupancy Class	Model Building Type								
		5	**8**	**12**	**15**	**18**	**21**	**24**	**28**	**33**
		S1H	S2H	S4H	S5H	C1H	C2H	C3H	PC2H	RM2H
3	RES3	39	1	2		8	24	23	3	
4	RES4	45	3	3		8	20	18	3	
5	RES5	15	5	10			30	40		
10	COM4	47	10	4		1	21	16	1	
11	COM5	47	10	4		1	21	16	1	
12	COM6	56	9	1		1	24	8	1	
13	COM7									
16	COM10									
23	AGR1									
25	GOV1	53	5	5		3	30	3	1	
28	EDU2	5	5	35			40	15		

* Refer to Table 3C.1 for states' classifications.

Table 3A.9: Distribution Percentage of Floor Area for Model Building Types within Each Building Occupancy Class, High Rise, 1950-1970, West Coast* (after ATC-13, 1985)

No.	Specific Occupancy Class	Model Building Type								
		5	**8**	**12**	**15**	**18**	**21**	**24**	**28**	**33**
		S1H	S2H	S4H	S5H	C1H	C2H	C3H	PC2H	RM2H
3	RES3	30	21	6		13	24		3	3
4	RES4	48	10	9		12	19		1	1
5	RES5	20	15	25		30	5			5
10	COM4	40	26	18		6	7		1	2
11	COM5	40	26	18		6	7		1	2
12	COM6	35	27	17		4	15		1	1
13	COM7									
16	COM10									
23	AGR1									
25	GOV1	46	13	22		10	8			1
28	EDU2	35	20	20		25				

* Refer to Table 3C.1 for states' classifications.

Table 3A.10: Distribution Percentage of Floor Area for Model Building Types within Each Building Occupancy Class, High Rise, Post-1970, West Coast* (after ATC-13, 1985)

No.	Specific Occupancy Class	Model Building Type								
		5	**8**	**12**	**15**	**18**	**21**	**24**	**28**	**33**
		S1H	S2H	S4H	S5H	C1H	C2H	C3H	PC2H	RM2H
3	RES3	44	6	5		18	20		5	2
4	RES4	56	10	6		16	9		2	1
5	RES5	25	18	20		37				
10	COM4	56	10	14		14	5		1	
11	COM5	54	10	15		15	5		1	
12	COM6	45	6	19		13	17			
13	COM7									
16	COM10									
23	AGR1									
25	GOV1	52	14	14		14	6			
28	EDU2	30	10	10		50				

* Refer to Table 3C.1 for states' classifications.

Table 3A.11: Distribution Percentage of Floor Area for Model Building Types within Each Building Occupancy Class, Low Rise, Mid-West*

No.	Specific Occup. Class	Model Building Type															
		1	2	3	6	9	10	13	16	19	22	25	26	29	31	34	36
		W1	W2	S1L	S2L	S3	S4L	S5L	C1L	C2L	C3L	PC1	PC2L	RM1L	RM2L	URML	MH
1	RES1	For State-Specific "Res1" Distribution, Refer to Table 3A.20															
2	RES2																100
3	RES3	75												2		23	
4	RES4	50												3	2	45	
5	RES5	20							4	13	2	22	4	2		33	
6	RES6	90														10	
7	COM1		30	2	4	11	6	7		5		5		2		28	
8	COM2		10	2	4	11	6	7	2	10	2	14	2	2		28	
9	COM3		30	2	4	11	6	7		5		5		2		28	
10	COM4		30	2	4	11	6	7		5		5		2		28	
11	COM5		30	2	4	11	6	7		5		5		2		28	
12	COM6				2	4	2	2	6	21	4	33	6	2		18	
13	COM7		30	2	4	11	6	7		5		5		2		28	
14	COM8		30	2	4	11	6	7		5		5		2		28	
15	COM9			2	6	14	8	10	4	13	2	22	4			15	
16	COM10			2	4	11	6	7	6	21	4	33	6				
17	IND1			5	10	25	13	17	2	7	2	12	2			5	
18	IND2		10	2	4	11	6	7	2	10	2	14	2	3		27	
19	IND3		10	2	4	11	6	7	2	10	2	14	2	3		27	
20	IND4			5	10	25	13	17	2	7	2	12	2			5	
21	IND5		10	2	4	11	6	7	2	10	2	14	2	2		28	
22	IND6		30	2	4	11	6	7		5		5		2		28	
23	AGR1		10	2	4	11	6	7	2	10	2	14	2	2		28	
24	REL1	30			3	5	3	4		5		5		2	2	41	
25	GOV1		15	14	21				7	6		4		3		30	
26	GOV2		14	7	17				4	12					3	43	
27	EDU1		10	5	12				5	7				11		50	
28	EDU2		14	6	12			2	8	11					10	37	

* Refer to Table 3C.1 for states' classifications.

Table 3A.12: Distribution Percentage of Floor Area for Model Building Types within Each Building Occupancy Class, Mid Rise, Mid-West*

No.	Specific Occupancy Class	Model Building Type										
		4	7	11	14	17	20	23	27	30	32	35
		S1M	S2M	S4M	S5M	C1M	C2M	C3M	PC2M	RM1M	RM2M	URMM
3	RES3		10	7	3	14	39		7		2	18
4	RES4		10	7	3	14	37	2	7		2	18
5	RES5					25	62	2	11			
6	RES6											
7	COM1	3	20	16	6	11	27	2	5		2	8
8	COM2		7	3		14	37	2	7		3	27
9	COM3	3	20	16	6	11	27	2	5		2	8
10	COM4	3	20	16	6	11	27	2	5		2	8
11	COM5	3	20	16	6	11	27	2	5		2	8
12	COM6	3	20	16	6	12	30	2	6			5
13	COM7	3	20	16	6	11	27	2	5		2	8
14	COM8	3	20	16	6	11	27	2	5		2	8
15	COM9											
16	COM10	2	14	10	4	17	43	2	8			
17	IND1											
18	IND2		7	3		14	37	2	7		3	27
19	IND3		7	3		14	37	2	7		3	27
20	IND4											
21	IND5		7	3		14	37	2	7		3	27
22	IND6											
23	AGR1		7	3		14	37	2	7		3	27
24	REL1	3	20	16	6	11	27	2	5		2	8
25	GOV1	20	24			11	9				5	31
26	GOV2											
28	EDU2	7	14			9	13				13	44

* Refer to Table 3C.1 for states' classifications.

Table 3A.13: Distribution Percentage of Floor Area for Model Building Types within Each Building Occupancy Class, High Rise, Mid-West*

No.	Specific Occup. Class	Model Building Type								
		5	8	12	15	18	21	24	28	33
		S1H	S2H	S4H	S5H	C1H	C2H	C3H	PC2H	RM2H
3	RES3	3	13	4		16	44	7	7	6
4	RES4	3	13	4		16	44	7	7	6
5	RES5					26	74			
10	COM4	7	29	9		12	32	4	4	3
11	COM5	7	29	9		12	32	4	4	3
12	COM6	7	29	9		13	36	2	2	2
13	COM7	7	29	9		12	32	4	4	3
16	COM10	5	19	6		18	52			
23	AGR1	2	6	2		16	44	11	11	8
25	GOV1									
28	EDU2									

* Refer to Table 3C.1 for states' classifications.

Table 3A.14: Distribution Percentage of Floor Area for Model Building Types within Each Building Occupancy Class, Low Rise, East Coast*

No.	Specific Occup. Class	Model Building Type															
		1	2	3	6	9	10	13	16	19	22	25	26	29	31	34	36
		W1	W2	S1L	S2L	S3	S4L	S5L	C1L	C2L	C3L	PC1	PC2L	RM1L	RM2L	URML	MH
1	RES1	For State-Specific “Res1” Distribution, Refer to Table 3A.21															
2	RES2																100
3	RES3	62			3				2	2				5	4	22	
4	RES4	48		5	4			4	8	4		3	3	3	3	15	
5	RES5	7		7	6			6	17	6	3	8	6	5	5	24	
6	RES6	22		11	8			8	8	3	2	4	3	5	4	22	
7	COM1		14	20	15	5		16	3	2		2		4	2	17	
8	COM2		10	21	15	7		16	3	2		2		3	4	17	
9	COM3		25	7	5	11		5	3	2		2		6	4	30	
10	COM4		26	11	8	4		9	4	2		3		5	4	24	
11	COM5		13	13	9	13		10	5	3		2	2	5	3	22	
12	COM6		2	22	15			18	10	4	2	5	4	3	2	13	
13	COM7		24	10	7	15		8	3	2		3		4	4	20	
14	COM8		19	19	13	6		15	3	2		2		3	3	15	
15	COM9		5	20	13	12	2	16	7	2		3	3	3	2	12	
16	COM10			10	7			8	30	11	6	14	12			2	
17	IND1		5	22	15	4	2	17	7	3		3	3	3	3	13	
18	IND2		10	15	9	15		11	5	3		2	2	4	5	19	
19	IND3		7	25	18	3		19	4	2		2	2	3	2	13	
20	IND4		7	26	19	3		20	3	2		2		2	3	13	
21	IND5		5	25	17	3	2	20	7	3		3	3		2	10	
22	IND6		10	21	14	7	2	16	5	2		2	2	2	3	14	
23	AGR1		48	8	6	12		7	2					3	2	12	
24	REL1	36		4	4			3	2	2		2		7	6	34	
25	GOV1		7	24	16	3		19	5	3		2	1	3	3	13	
26	GOV2		8	16	11	4		13	8	3	2	4	3	4	5	19	
27	EDU1		13	17	13			13	5	3		2	2	5	5	22	
28	EDU2		4	18	13			14	8	3	2	4	3	5	4	22	

* Refer to Table 3C.1 for states' classifications.

Table 3A.15: Distribution Percentage of Floor Area for Model Building Types within Each Building Occupancy Class, Mid Rise, East Coast*

No.	Specific Occupancy Class	Model Building Type										
		4	7	11	14	17	20	23	27	30	32	35
		S1M	S2M	S4M	S5M	C1M	C2M	C3M	PC2M	RM1M	RM2M	URMM
3	RES3	3	4			6	3		14		13	57
4	RES4	9	12		3	18	9	2	11		7	29
5	RES5	7	10		3	23	11	3	12		5	26
6	RES6											
7	COM1	23	29	2	8	5	3		5		5	20
8	COM2	23	30	3	8	4	3		5		5	19
9	COM3	10	13		3	5	4		11		10	44
10	COM4	14	19	2	5	7	4		9		7	33
11	COM5	15	21	2	6	8	5		8		6	29
12	COM6	21	27	2	8	12	6	2	7		2	13
13	COM7	15	20	2	5	7	4		9		6	32
14	COM8	22	30	3	8	5	3		5		5	19
15	COM9											
16	COM10	10	13		3	38	17	6	11			2
17	IND1											
18	IND2	22	28	2	8	10	5	2	6		3	14
19	IND3	25	32	3	9	6	4		4		3	14
20	IND4											
21	IND5	24	32	3	9	9	6		5		2	10
22	IND6											
23	AGR1	19	25	2	7	4	2		7		6	28
24	REL1	5	9		2	4	3		12		12	53
25	GOV1	24	30	3	9	7	5		5		3	14
26	GOV2											
28	EDU2	17	23	2	6	10	5	2	8		4	23

***** Refer to Table 3C.1 for states' classifications.

Table 3A.16: Distribution Percentage of Floor Area for Model Building Types within Each Building Occupancy Class, High Rise, East Coast*

No.	Specific Occup. Class	Model Building Type								
		5	8	12	15	18	21	24	28	33
		S1H	S2H	S4H	S5H	C1H	C2H	C3H	PC2H	RM2H
3	RES3	8	21	8		34	17	2	5	5
4	RES4	8	21	8		34	17	2	5	5
5	RES5	6	16	6		40	20	3	5	4
10	COM4	15	36	15		15	8		2	9
11	COM5	15	36	15		15	8		2	9
12	COM6	14	35	14		17	8	2	2	8
13	COM7	15	38	15		14	8		2	8
16	COM10	5	12	5		43	21	4	6	4
23	AGR1	7	4	18		20	42			9
25	GOV1									
28	EDU2									

* Refer to Table 3C.1 for states' classifications.

Table 3A.17: Distribution Percentage of Floor Area for Model Building Types within "RES1" Building Occupancy Class, Pre-1950, West Coast

State FIPS*	State Abbreviation	State	Model Building Type					
			1	9	13	19	29	34
			W1	S3	S5L	C2L	RM1L	URML
02	AK	Alaska	99			1		
04	AZ	Arizona	60				25	16
06	CA	California	99				1	0
08	CO	Colorado	76				15	9
15	HI	Hawaii	92			1	4	3
16	ID	Idaho	95				3	2
30	MT	Montana	98				1	1
35	NM	New Mexico	74				16	10
32	NV	Nevada	97				2	1
41	OR	Oregon	99				1	
49	UT	Utah	82				11	7
53	WA	Washington	98				1	1
56	WY	Wyoming	92				5	3

* State FIPS are two digit unique number representative of each state and US territory. Refer to Table 3C.1 of Appendix C for a complete list of State FIPS.

Table 3A.18: Distribution Percentage of Floor Area for Model Building Types within "RES1" Building Occupancy Class, 1950-1970, West Coast

State FIPS	State Abbreviation	State	Model Building Type 1	9	13	19	29	34
			W1	S3	S5L	C2L	RM1L	URML
02	AK	Alaska	99			1		
04	AZ	Arizona	60				36	4
06	CA	California	99				1	0
08	CO	Colorado	76				21	3
15	HI	Hawaii	92			1	6	1
16	ID	Idaho	95				4	1
30	MT	Montana	98				2	
35	NM	New Mexico	74				23	3
32	NV	Nevada	97				3	
41	OR	Oregon	99				1	
49	UT	Utah	82				16	2
53	WA	Washington	98				2	
56	WY	Wyoming	92				7	1

Table 3A.19: Distribution Percentage of Floor Area for Model Building Types within "RES1" Building Occupancy Class, Post-1970, West Coast

State FIPS	State Abbreviation	State	Model Building Type 1	9	13	19	29	34
			W1	S3	S5L	C2L	RM1L	URML
02	AK	Alaska	99			1		
04	AZ	Arizona	60				40	
06	CA	California	99				1	0
08	CO	Colorado	76				24	
15	HI	Hawaii	92			1	7	
16	ID	Idaho	95				5	
30	MT	Montana	98				2	
35	NM	New Mexico	74				26	
32	NV	Nevada	97				3	
41	OR	Oregon	99				1	
49	UT	Utah	82				18	
53	WA	Washington	98				2	
56	WY	Wyoming	92				8	

Table 3A.20: Distribution Percentage of Floor Area for Model Building Types within "RES1" Building Occupancy Class, Mid-West

State FIPS	State Abbreviation	State	Model Building Type		
			1	19	34
			W1	C2L	URML
05	AR	Arkansas	87		13
19	IA	Iowa	92		8
17	IL	Illinois	77	1	22
18	IN	Indiana	80		20
20	KS	Kansas	91		9
21	KY	Kentucky	88		12
22	LA	Louisiana	89		11
26	MI	Michigan	86		14
27	MN	Minnesota	95	1	4
29	MO	Missouri	76		24
28	MS	Mississippi	94		6
38	ND	North Dakota	98		2
31	NE	Nebraska	89	1	10
39	OH	Ohio	76		24
40	OK	Oklahoma	71		29
46	SD	South Dakota	97		3
47	TN	Tennessee	90		10
48	TX	Texas	100		
55	WI	Wisconsin	90		10

Table 3A.21: Distribution Percentage of Floor Area for Model Building Types within “RES1” Building Occupancy Class, East Coast

State FIPS	State Abbreviation	State	Model Building Type 1 W1	19 C2L	34 URML
01	AL	Alabama	95		5
09	CT	Connecticut	96		4
11	DC	District of Columbia	21	3	76
10	DE	Delaware	71	1	28
12	FL	Florida	25	5	70
13	GA	Georgia	93		7
25	MA	Massachusetts	96		4
24	MD	Maryland	71	1	28
23	ME	Maine	99		1
37	NC	North Carolina	90		10
33	NH	New Hampshire	97	1	2
34	NJ	New Jersey	91		9
36	NY	New York	85	1	14
42	PA	Pennsylvania	66		34
44	RI	Rhode Island	98		2
45	SC	South Carolina	92		8
51	VA	Virginia	75		25
50	VT	Vermont	96	2	2
54	WV	West Virginia	72		28

APPENDIX 3B
Essential Facilities

Table 3B.1: Distribution Percentage of Floor Area for Specific Occupancy Classes within each General Occupancy Class

Specific Occupancy Class			General Occupancy Class		
			Medical Care	Emergency Response	Schools
No.	Label	Occupancy Class	1	2	3
1	EFHS	Small Hospital	X		
2	EFHM	Medium Hospital	X		
3	EFHL	Large Hospital	X		
4	EFMC	Medical Clinics	X		
5	EFFS	Fire Station		X	
6	EFPS	Police Station		X	
7	EFEO	Emergency Operation Centers		X	
8	EFS1	Grade Schools			X
9	EFS2	Colleges/ Universities			X

Table 3B.2: Distribution Percentage of Floor Area for Model Building Types within Each Building Occupancy Class, Low Rise, Pre-1950, West Coast* (after ATC-13, 1985)

No.	Specific Occup. Class	Model Building Type														
		1	2	3	6	9	10	13	16	19	22	25	26	29	31	34
		W1	W2	S1L	S2L	S3	S4L	S5L	C1L	C2L	C3L	PC1	PC2L	RM1L	RM2L	URML
1	EFHS		8	5	2	11		11		27	2	1		27		6
2	EFHM		8	5	2	11		11		27	2	1		27		6
3	EFHL		8	5	2	11		11		27	2	1		27		6
4	EFMC		8	5	2	11		11		27	2	1		27		6
5	EFFS	45					2			37				3		13
6	EFPS	45					2			37				3		13
7	EFEO	45					2			37				3		13
8	EFS1	11		6		3	3	21		21	4			9		22
9	EFS2	2		5	10		5	15		20				20	5	18

Table 3B.3: Distribution Percentage of Floor Area for Model Building Types within Each Building Occupancy Class, Low Rise, 1950-1970, West Coast* (after ATC-13, 1985)

No.	Specific Occup. Class	Model Building Type														
		1	**2**	**3**	**6**	**9**	**10**	**13**	**16**	**19**	**22**	**25**	**26**	**29**	**31**	**34**
		W1	W2	S1L	S2L	S3	S4L	S5L	C1L	C2L	C3L	PC1	PC2L	RM1L	RM2L	URML
1	EFHS		32	5	2	4	3			16	6			28	4	
2	EFHM		32	5	2	4	3			16	6			28	4	
3	EFHL		32	5	2	4	3			16	6			28	4	
4	EFMC		32	5	2	4	3			16	6			28	4	
5	EFFS	50								13		7		20	10	
6	EFPS	50								13		7		20	10	
7	EFEO	50								13		7		20	10	
8	EFS1	25		3	4	5	4			20		4	2	29	4	
9	EFS2	5		2	12		5			20				50	6	

* Refer to Table 3C.1 for states' classifications.

Table 3B.4: Distribution Percentage of Floor Area for Model Building Types within Each Building Occupancy Class, Low Rise, Post-1970, West Coast* (after ATC-13, 1985)

No.	Specific Occup. Class	Model Building Type														
		1	**2**	**3**	**6**	**9**	**10**	**13**	**16**	**19**	**22**	**25**	**26**	**29**	**31**	**34**
		W1	W2	S1L	S2L	S3	S4L	S5L	C1L	C2L	C3L	PC1	PC2L	RM1L	RM2L	URML
1	EFHS		31	6	1	1	7		4	13		7		28	2	
2	EFHM		31	6	1	1	7		4	13		7		28	2	
3	EFHL		31	6	1	1	7		4	13		7		28	2	
4	EFMC		31	6	1	1	7		4	13		7		28	2	
5	EFFS	40		3	7		23			10			7	3	7	
6	EFPS	40		3	7		23			10			7	3	7	
7	EFEO	40		3	7		23			10			7	3	7	
8	EFS1	24		9	6	1	5		3	16	3	4	3	21	5	
9	EFS2	5		10	10		5			20		5		40	5	

Table 3B.5: Distribution Percentage of Floor Area for Model Building Types within Each Building Occupancy Class, Mid Rise, Pre-1950, West Coast* (after ATC-13, 1985)

No.	Specific Occupancy Class	Model Building Type										
		4	7	11	14	17	20	23	27	30	32	35
		S1M	S2M	S4M	S5M	C1M	C2M	C3M	PC2M	RM1M	RM2M	URMM
1	EFHS	18	4	6		1	35	19		8		9
2	EFHM	18	4	6		1	35	19		8		9
3	EFHL	18	4	6		1	35	19		8		9
4	EFMC	18	4	6		1	35	19		8		9
5	EFFS											
6	EFPS											
7	EFEO											
9	EFS2	10		20			60	3		5		2

* Refer to Table 3C.1 for states' classifications.

Table 3B.6: Distribution Percentage of Floor Area for Model Building Types within Each Building Occupancy Class, Mid Rise, 1950-1970, West Coast* (after ATC-13, 1985)

No.	Specific Occupancy Class	Model Building Type										
		4	7	11	14	17	20	23	27	30	32	35
		S1M	S2M	S4M	S5M	C1M	C2M	C3M	PC2M	RM1M	RM2M	URMM
1	EFHS	14	10	14		5	23		3	23	8	
2	EFHM	14	10	14		5	23		3	23	8	
3	EFHL	14	10	14		5	23		3	23	8	
4	EFMC	14	10	14		5	23		3	23	8	
5	EFFS	5	10	10		5	60				10	
6	EFPS	5	10	10		5	60				10	
7	EFEO	5	10	10		5	60				10	
9	EFS2	20		15		5	35			15	10	

Table 3B.7: Distribution Percentage of Floor Area for Model Building Types within Each Building Occupancy Class, Mid Rise, Post-1970, West Coast* (after ATC-13, 1985)

No.	Specific Occupancy Class	Model Building Type										
		4	7	11	14	17	20	23	27	30	32	35
		S1M	S2M	S4M	S5M	C1M	C2M	C3M	PC2M	RM1M	RM2M	URMM
1	EFHS	25	9	15		10	33		1	6	1	
2	EFHM	25	9	15		10	33		1	6	1	
3	EFHL	25	9	15		10	33		1	6	1	
4	EFMC	25	9	15		10	33		1	6	1	
5	EFFS	25	20	35			20					
6	EFPS	25	20	35			20					
7	EFEO	25	20	35			20					
9	EFS2	20	5	10		25	25			10	5	

* Refer to Table 3C.1 for states' classifications.

Table 3B.8: Distribution Percentage of Floor Area for Model Building Types within Each Building Occupancy Class, High Rise, Pre-1950, West Coast* (after ATC-13, 1985)

No.	Specific Occupancy Class	Model Building Type								
		5	8	12	15	18	21	24	28	33
		S1H	S2H	S4H	S5H	C1H	C2H	C3H	PC2H	RM2H
1	EFHS	56	9	1		1	24	8	1	
2	EFHM	56	9	1		1	24	8	1	
3	EFHL	56	9	1		1	24	8	1	
4	EFMC	56	9	1		1	24	8	1	
9	EFS2	5	5	35			40	15		

Table 3B.9: Distribution Percentage of Floor Area for Model Building Types within Each Building Occupancy Class, High Rise, 1950-1970, West Coast* (after ATC-13, 1985)

No.	Specific Occupancy Class	Model Building Type								
		5	8	12	15	18	21	24	28	33
		S1H	S2H	S4H	S5H	C1H	C2H	C3H	PC2H	RM2H
1	EFHS	35	27	17		4	15		1	1
2	EFHM	35	27	17		4	15		1	1
3	EFHL	35	27	17		4	15		1	1
4	EFMC	35	27	17		4	15		1	1
9	EFS2	35	20	20		25				

Table 3B.10: Distribution Percentage of Floor Area, for Model Building Types within Each Building Occupancy Class, High Rise, Post-1970, West Coast* (after ATC-13, 1985)

No.	Specific Occupancy Class	Model Building Type								
		5	8	12	15	18	21	24	28	33
		S1H	S2H	S4H	S5H	C1H	C2H	C3H	PC2H	RM2H
1	EFHS	45	6	19		13	17			
2	EFHM	45	6	19		13	17			
3	EFHL	45	6	19		13	17			
4	EFMC	45	6	19		13	17			
9	EFS2	30	10	10		50				

* Refer to Table 3C.1 for states' classifications.

Table 3B.11: Distribution Percentage of Floor Area for Model Building Types within Each Building Occupancy Class, Low Rise, Mid-West*

No.	Specific Occup. Class	Model Building Type														
		1	2	3	6	9	10	13	16	19	22	25	26	29	31	34
		W1	W2	S1L	S2L	S3	S4L	S5L	C1L	C2L	C3L	PC1	PC2L	RM1L	RM2L	URML
1	EFHS		30	2	4	11	6	7		5		5		2		28
2	EFHM				2	4	2	2	6	21	4	33	6	2		18
3	EFHL				2	4	2	2	6	21	4	33	6	2		18
4	EFMC		30	2	4	11	6	7		5		5		2		28
5	EFFS		14	7	17				4	12					3	43
6	EFPS		14	7	17				4	12					3	43
7	EFEO		14	7	17				4	12					3	43
8	EFS1		10	5	12				5	7				11		50
9	EFS2		14	6	12			2	8	11					10	37

Table 3B.12: Distribution Percentage of Floor Area for Model Building Types within Each Building Occupancy Class, Mid Rise, Mid-West*

No.	Specific Occupancy Class	Model Building Type										
		4	7	11	14	17	20	23	27	30	32	35
		S1M	S2M	S4M	S5M	C1M	C2M	C3M	PC2M	RM1M	RM2M	URMM
1	EFHS	3	20	16	6	11	27	2	5		2	8
2	EFHM	3	20	16	6	12	30	2	6			5
3	EFHL	3	20	16	6	12	30	2	6			5
4	EFMC	3	20	16	6	11	27	2	5		2	8
5	EFFS											
6	EFPS											
7	EFEO											
9	EFS2	7	14			9	13				13	44

* Refer to Table 3C.1 for states' classifications.

Table 3B.13: Distribution Percentage of Floor Area for Model Building Types within Each Building Occupancy Class, High Rise, Mid-West*

No.	Specific Occupancy Class	Model Building Type								
		5	8	12	15	18	21	24	28	33
		S1H	S2H	S4H	S5H	C1H	C2H	C3H	PC2H	RM2H
1	EFHS	7	29	9		12	32	4	4	3
2	EFHM	7	29	9		13	36	2	2	2
3	EFHL	7	29	9		13	36	2	2	2
4	EFMC	7	29	9		12	32	4	4	3
7	EFEO									
9	EFS2									

Table 3B.14: Distribution Percentage of Floor Area for Model Building Types within Each Building Occupancy Class, Low Rise, East Coast*

No.	Specific Occup. Class	Model Building Type														
		1	2	3	6	9	10	13	16	19	22	25	26	29	31	34
		W1	W2	S1L	S2L	S3	S4L	S5L	C1L	C2L	C3L	PC1	PC2L	RM1L	RM2L	URML
1	EFHS		24	10	7	15		8	3	2		3		4	4	20
2	EFHM		2	22	15			18	10	4	2	5	4	3	2	13
3	EFHL		2	22	15			18	10	4	2	5	4	3	2	13
4	EFMC		24	10	7	15		8	3	2		3		4	4	20
5	EFFS		8	16	11	4		13	8	3	2	4	3	4	5	19
6	EFPS		8	16	11	4		13	8	3	2	4	3	4	5	19
7	EFEO		8	16	11	4		13	8	3	2	4	3	4	5	19
8	EFS1		13	17	13			13	5	3		2	2	5	5	22
9	EFS2		4	18	13			14	8	3	2	4	3	5	4	22

* Refer to Table 3C.1 for states' classifications.

Table 3B.15: Distribution Percentage of Floor Area for Model Building Types within Each Building Occupancy Class, Mid Rise, East Coast*

No.	Specific Occupancy Class	Model Building Type										
		4	**7**	**11**	**14**	**17**	**20**	**23**	**27**	**30**	**32**	**35**
		S1M	S2M	S4M	S5M	C1M	C2M	C3M	PC2M	RM1M	RM2M	URMM
1	EFHS	15	20	2	5	7	4		9		6	32
2	EFHM	21	27	2	8	12	6	2	7		2	13
3	EFHL	21	27	2	8	12	6	2	7		2	13
4	EFMC	15	20	2	5	7	4		9		6	32
5	EFFS											
6	EFPS											
7	EFEO											
9	EFS2	17	23	2	6	10	5	2	8		4	23

Table 3B.16: Distribution Percentage of Floor Area for Model Building Types within Each Building Occupancy Class, High Rise, East Coast*

No.	Specific Occupancy Class	Model Building Type								
		5	**8**	**12**	**15**	**18**	**21**	**24**	**28**	**33**
		S1H	S2H	S4H	S5H	C1H	C2H	C3H	PC2H	RM2H
1	EFHS	15	38	15		14	8		2	8
2	EFHM	14	35	14		17	8	2	2	8
3	EFHL	14	35	14		17	8	2	2	8
4	EFMC	15	38	15		14	8		2	8
7	EFEO									
9	EFS2									

- Refer to Table 3C.1 for states' classifications.

APPENDIX 3C

States' Classifications

Table 3C.1: Regional Distribution of States

State Fips	State Abbreviation	State Name	Group
02	AK	Alaska	West
01	AL	Alabama	East
05	AR	Arkansas	Mid-West
04	AZ	Arizona	West
06	CA	California	West
08	CO	Colorado	West
09	CT	Connecticut	East
11	DC	District of Columbia	East
10	DE	Delaware	East
12	FL	Florida	East
13	GA	Georgia	East
15	HI	Hawaii	West
19	IA	Iowa	Mid-West
16	ID	Idaho	West
17	IL	Illinois	Mid-West
18	IN	Indiana	Mid-West
20	KS	Kansas	Mid-West
21	KY	Kentucky	Mid-West
22	LA	Louisiana	Mid-West
25	MA	Massachusetts	East
24	MD	Maryland	East
23	ME	Maine	East
26	MI	Michigan	Mid-West
27	MN	Minnesota	Mid-West
29	MO	Missouri	Mid-West
28	MS	Mississippi	Mid-West
30	MT	Montana	West
37	NC	North Carolina	East
38	ND	North Dakota	Mid-West
31	NE	Nebraska	Mid-West
33	NH	New Hampshire	East
34	NJ	New Jersey	East
35	NM	New Mexico	West
32	NV	Nevada	West
36	NY	New York	East
39	OH	Ohio	Mid-West
40	OK	Oklahoma	Mid-West
41	OR	Oregon	West
42	PA	Pennsylvania	East
44	RI	Rhode Island	East

Table 3C.1(cont.): Regional Distribution of States

State Fips	State Abbreviation	State Name	Group
45	SC	South Carolina	East
46	SD	South Dakota	Mid-West
47	TN	Tennessee	Mid-West
48	TX	Texas	Mid-West
49	UT	Utah	West
51	VA	Virginia	East
50	VT	Vermont	East
53	WA	Washington	West
55	WI	Wisconsin	Mid-West
54	WV	West Virginia	East
56	WY	Wyoming	West
60	AS	American Samoa	West
66	GU	Guam	West
69	MR	Northern Mariana Islands	West
72	PR	Puerto Rico	East
78	VI	Virgin Islands	East

Chapter 4
Potential Earth Science Hazards (PESH)

Potential earth science hazards (PESH) include ground motion, ground failure (i.e., liquefaction, landslide and surface fault rupture) and tsunami/seiche. Methods for developing estimates of ground motion and ground failure are discussed in the following sections. Tsunami/seiche can be included in the Methodology in the form of user-supplied inundation maps as discussed in Chapter 9. The Methodology, highlighting the PESH component, is shown in Flowchart 4.1.

4.1 Ground Motion

4.1.1 Introduction

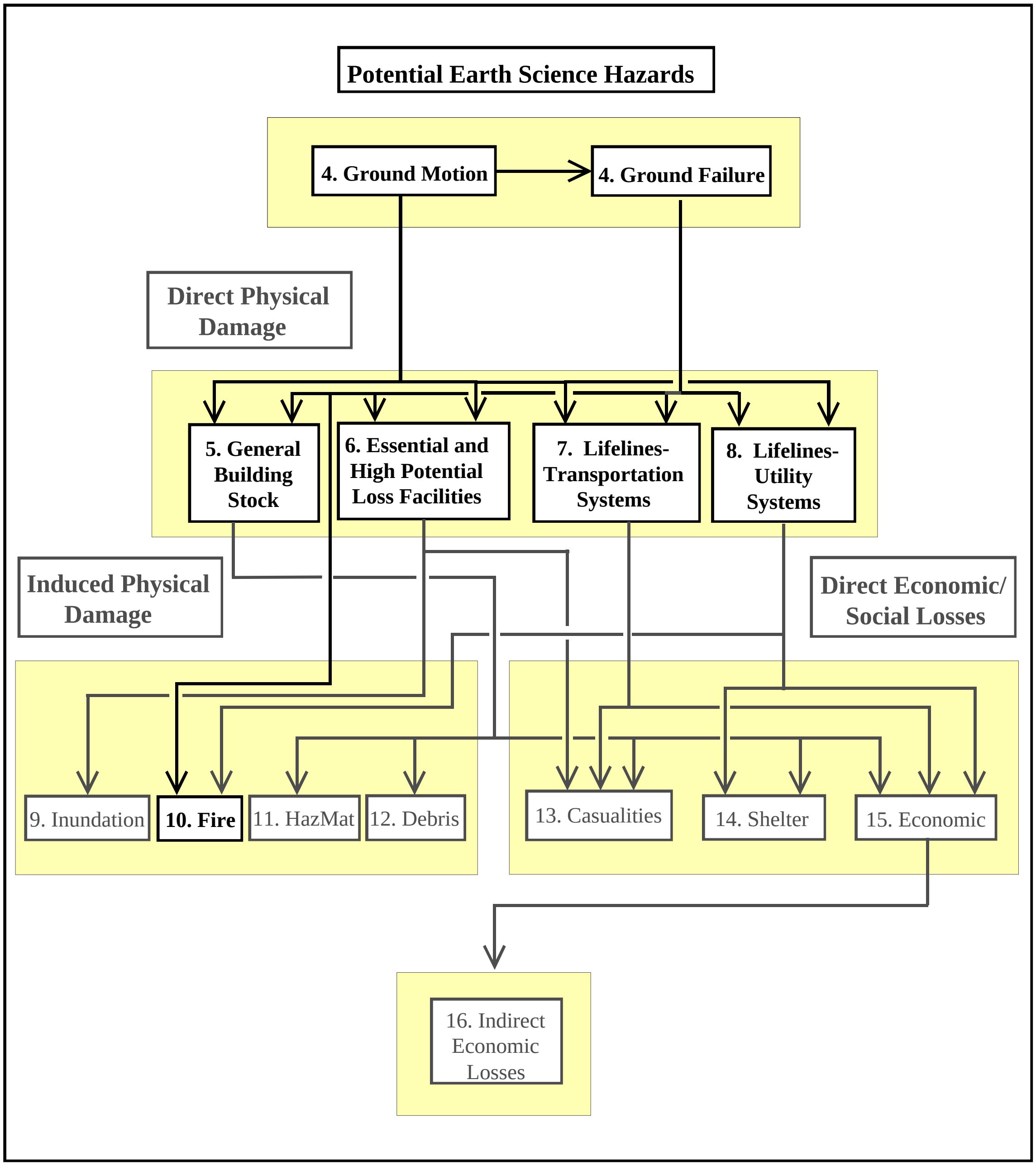
Ground motion estimates are generated in the form of GIS-based contour maps and location-specific seismic demands stored in relational databases. Ground motion is characterized by: (1) spectral response, based on a standard spectrum shape, (2) peak ground acceleration and (3) peak ground velocity. The spatial distribution of ground motion can be determined using one of the following methods or sources:

- Deterministic ground motion analysis (Methodology calculation)
- USGS probabilistic ground motion maps (maps supplied with **HAZUS-MH**)
- Other probabilistic or deterministic ground motion maps (user-supplied maps)

Deterministic seismic ground motion demands are calculated for user-specified scenario earthquakes (Section 4.1.2.1). The attenuation relationships provided with the Methodology include all five of the Next Generation Attenuation (NGA) Models developed for the Western United States (WUS) and seven ground-motion prediction equations (GMPEs) for the Central and Eastern United States (CEUS). It is expected by late 2012/early 2013 that the NGA Models will be developed/finalized for CEUS and therefore will be available to include in HAZUS as well.

In the Methodology's probabilistic analysis procedure, the ground shaking demand is characterized by spectral contour maps developed by the United States Geological Survey (USGS) as part of 2008 update of the National Seismic Hazard Maps (http://earthquake.usgs.gov/hazards/products/conterminous/2008/update_200812.php). USGS probabilistic seismic hazard maps are revised about every six years to reflect newly published or thoroughly reviewed earthquake science and to keep pace with regular updates of the building code.

The HAZUS Methodology includes maps for eight probabilistic hazard levels: ranging from ground shaking with a 39% probability of being exceeded in 50 years (100 year return period) to the ground shaking with a 2% probability of being exceeded in 50 years (2500 year return period). The USGS data compiled in HAZUS is for ground shaking demand corresponding to V_S^{30} of 760 m/s (Site Class B / C). For other sites, the Methodology amplifies the shaking based on local soil conditions.



Flowchart 4.1: Ground Motion and Ground Failure Relationship to other Modules of the Earthquake Loss Estimation Methodology

User-supplied peak ground acceleration (PGA) and spectral acceleration contour maps may also be used with **HAZUS-MH** (Section 4.1.2.1). In this case, the user must provide all contour maps in a pre-defined digital format (as specified in the *User's Manual*). As stated in Section 4.1.2.1, the Methodology assumes that user-supplied maps reflect soil amplification.

4.1.1.1 Form of Ground Motion Estimates / Site Effects

Ground motion estimates are represented by: (1) contour maps and (2) location-specific values of ground shaking demand. For computational efficiency and improved accuracy, earthquake losses are generally computed using location-specific estimates of ground shaking demand. For general building stock the analysis has been simplified so that ground motion demand is computed at the centroid of a census tract. However, contour maps are also developed to provide pictorial representations of the variation in ground motion demand within the study region. When ground motion is based on either USGS or user-supplied maps, location-specific values of ground shaking demand are interpolated between PGA, PGV or spectral acceleration contours, respectively.

Elastic response spectra (5% damping) are used by the Methodology to characterize ground shaking demand. These spectra all have the same "standard" format defined by a PGA value (at zero period) and spectral response at a period of 0.3 second (acceleration domain) and spectral response at a period of 1.0 second (velocity domain). Ground shaking demand is also defined by peak ground velocity (PGV).

4.1.1.2 Input Requirements and Output Information

For computation of ground shaking demand, the following inputs are required:

- **Scenario Basis** - The user must select the basis for determining ground shaking demand from one of three options: (1) a deterministic calculation, (2) probabilistic maps, supplied with the Methodology, or (3) user-supplied maps. For deterministic calculation of ground shaking, the user specifies a scenario earthquake magnitude and location. In some cases, the user may also need to specify certain source attributes required by the attenuation relationships supplied with the Methodology.
- **Attenuation Relationship** - For deterministic calculation of ground shaking, the user selects an appropriate attenuation relationship from those supplied with the Methodology. Attenuation relationships are based on the geographic location of the study region (Western United States vs. Central Eastern United States) and on the type of fault for WUS sources. WUS regions include locations in, or west of, the Rocky Mountains, Hawaii and Alaska. Figure 4-1 shows the regional separation of WUS and CEUS locations as defined by USGS in the development of the National Seismic Hazard Maps.

  For WUS sources, the attenuation functions predict ground shaking based on source type, including: (1) strike-slip (SS) faults, (2) reverse-slip (R) faults, (3) normal (N) faults (4) Interface events and (5) Interslab events. The Methodology provides combinations of attenuation functions for the WUS and CEUS, respectively, where the default weights are consistent with those used in compiling the 2008 USGS probabilistic data (Peterson et al., 2008, http://pubs.usgs.gov/of/2008/1128/).

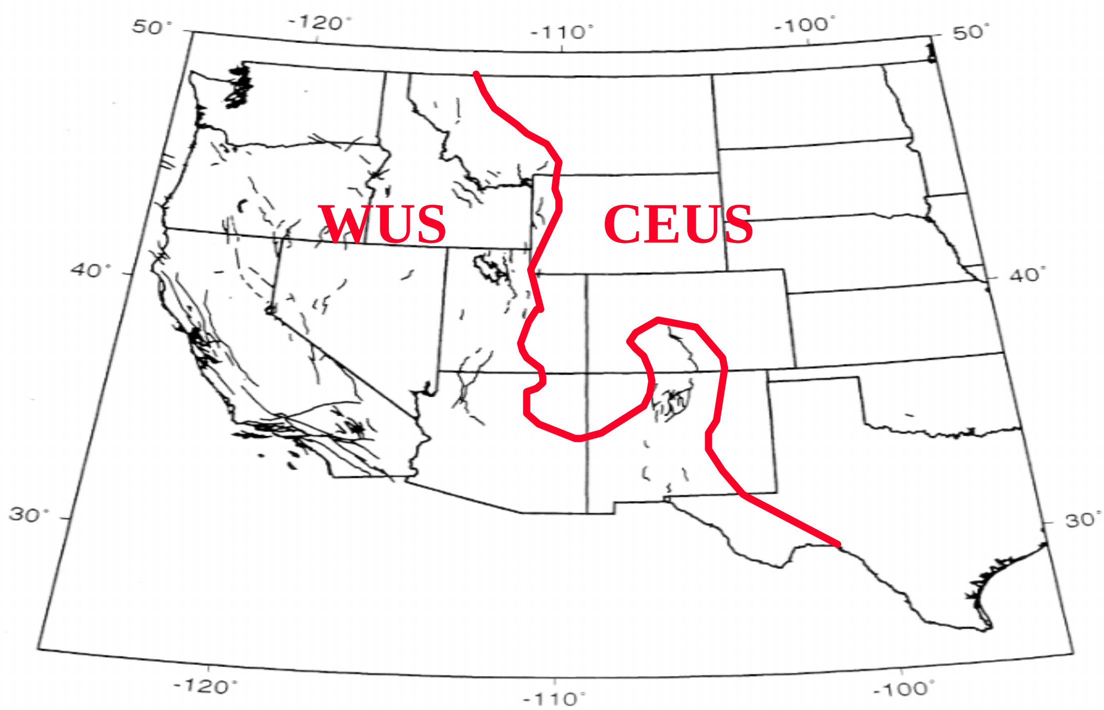


Figure 4.1 Boundaries Between WUS and CEUS Locations.

- **Soil Map -** The user may supply a detailed soil map to account for local site conditions. This map must identify soil type using a scheme that is based on, or can be related to, the site class definitions of the 1997 *NEHRP Provisions* (Section 4.1.2.4), and must be in pre-defined digital format (as specified in the *User's Manual*). In the absence of a soil map, **HAZUS-MH** will use the amplified ground motion demand assuming Site Class D soil at all sites. The user can also modify the assumed Site Class soil type for all sites by modifying the analysis parameters in **HAZUS-MH** (i.e. change the Site Class from D to A, B, C or E).

4.1.2 Description of Methods

The description of the methods for calculating ground shaking is divided into five separate areas:

- Basis for ground shaking (Section 4.1.2.1)
- Standard shape of response spectra (Section 4.1.2.2)
- Attenuation of ground shaking (Section 4.1.2.3)
- Distance measurement used with attenuation relationships (Section 4.1.2.4)
- Amplification of ground shaking - local site conditions (Section 4.1.2.5)

4.1.2.1 Basis for Ground Shaking

The methodology supports three options as the basis for ground shaking:

- Deterministic calculation of scenario earthquake ground shaking
- Probabilistic seismic hazard maps (USGS)
- User-supplied seismic hazard maps

<u>Deterministic Calculation of Scenario Earthquake Ground Shaking</u>
For deterministic calculation of the scenario event, the user specifies the location (e.g., epicenter) and magnitude of the scenario earthquake. The Methodology provides three options for selection of an appropriate scenario earthquake location. The user can either: (1) specify an event based on a database of WUS seismic sources (faults), (2) specify an event based on a database of historical earthquake epicenters, or (3) specify an event based on an arbitrary choice of the epicenter. These options are described below.

<u>Seismic Source Database (WUS Fault Map)</u>
For the WUS, the Methodology provides a database of seismic sources (fault segments) developed by the USGS, the California Geological Survey (CGS) and the Nevada Bureau of Mines and Geology (NBMG). The user accesses the database map (using **HAZUS-MH**) and selects a magnitude and epicenter on one of the identified fault segments. The database includes information on fault segment type, location, orientation and geometry (e.g., depth, width and dip angle), as well as on each fault segment's seismic potential (e.g., maximum moment).

The Methodology computes the expected values of surface and subsurface fault rupture length. Fault rupture length is based on the relationship of Wells and Coppersmith (1994) given below:

$$\log_{10}(L) = a + b \cdot M \tag{4-1}$$

Where: L is the rupture length (km)
M is the moment magnitude of the earthquake

Table 4.1 Regression Coefficients of Fault Rupture Relationship of Wells and Coppersmith (1994)

Rupture Type	Fault Type	a	b
Surface	Strike Slip	-3.55	0.74
	Reverse	-2.86	0.63
	All	-3.22	0.69
Subsurface	Strike Slip	-2.57	0.62
	Reverse	-2.42	0.58
	All	-2.44	0.59

Fault rupture is assumed to be of equal length on each side of the epicenter, provided the calculated rupture length is available in both directions along the specified fault segment.

If the epicenter location is less than one-half of the rupture length from an end point of the fault segment (e.g., the epicenter is located at or near an end of the fault segment), then fault rupture length is truncated so that rupture does not extend past the end of the fault segment. If the calculated rupture length exceeds the length of the fault segment, then the entire fault segment is assumed to rupture between its end points.

Historical Earthquake Database (Epicenter Map)

The Methodology software provides a database of historical earthquakes developed from three sources (Composite Earthquake Catalog, 2002, Earthquake Data Base, 2002, Earthquake Seismicity Catalog, 1996) and contains over 8,000 records. The database has been sorted to remove historical earthquakes with magnitudes less than 5.0. The user accesses the database via **HAZUS-MH** and selects a historical earthquake epicenter which includes location, depth and magnitude information.

For the WUS, the attenuation relationships require the user to specify the type, dip angle and orientation of the fault associated with the selected epicenter. The Methodology computes the expected values of surface and subsurface fault rupture length using Equation (4-1). Fault rupture is assumed to be of equal length on each side of the epicenter. For the CEUS, the attenuation relationships utilize the epicenter location and depth.

Arbitrary Event

Under this option, the user specifies a scenario event magnitude and arbitrary epicenter (using **HAZUS-MH**). For the WUS, the user must also supply the type, dip angle and orientation of the fault associated with the arbitrary epicenter. The Methodology computes the fault rupture length based on Equation (4-1) and assumes fault rupture to be of equal length on each side of the epicenter. For the CEUS the user must supply the depth of the hypocenter.

Probabilistic Seismic Hazard Maps (USGS)

The Methodology includes probabilistic seismic hazard contour maps developed by the USGS for the 2008 update of the National Seismic Hazard Maps (Peterson et al., 2008, http://pubs.usgs.gov/of/2008/1128/).

The USGS maps provide estimates of PGA and spectral acceleration at periods of 0.1, 0.2, 0.3, 0.75, 1.0, 2.0, 3.0, 4.0, and 5.0 second respectively and for different exceedence probabilities. In HAZUS, only PGA and spectral acceleration at periods of 0.3 second and 1.0 second are needed. In addition, ground shaking estimates are extracted for eight exceedence probabilities: ranging from the ground shaking with a 39% probability of being exceeded in 50 years to ground shaking with a 2% probability of being exceeded in 50 years. In terms of mean return periods, the hazard levels range from 100 years to 2500 years.

<u>User-Supplied Seismic Hazard Maps</u>

The Methodology allows the user to supply PGA and spectral acceleration contour maps of ground shaking in a pre-defined digital format (as specified in the **HAZUS-MH** *User's Manual*). This option permits the user to develop a scenario event that could not be described adequately by the available attenuation relationships, or to replicate historical earthquakes (e.g., 1994 Northridge Earthquake). The maps of PGA, PGV and spectral acceleration (periods of 0.3 and 1.0 second) must be provided. The Methodology software assumes these ground motion maps include soil amplification, thus no soil map is required.

If only PGA contour maps are available, the user must develop the other required maps. One approach that can help achieve that is to use the spectral acceleration response factors given in Table 4.2.

4.1.2.2 Standard Shape of the Response Spectra

The Methodology characterizes ground shaking using a standardized response spectrum shape, as shown in Figure 4.2. The standardized shape consists of four parts: peak ground acceleration (PGA), a region of constant spectral acceleration at periods from zero seconds to T_{AV} (seconds), a region of constant spectral velocity at periods from T_{AV} to T_{VD} (seconds) and a region of constant spectral displacement for periods of T_{VD} and beyond.

In Figure 4.2, spectral acceleration is plotted as a function of spectral displacement (rather than as a function of period). This is the format of response spectra used for evaluation of damage to buildings (Chapter 5) and essential facilities (Chapter 6). Equation (4-2) may be used to convert spectral displacement (inches), to period (seconds) for a given value of spectral acceleration (units of g), and Equation (4-3) may be used to convert spectral acceleration (units of g) to spectral displacement (inches) for a given value of period.

$$T = 0.32\sqrt{\frac{S_D}{S_A}} \tag{4-2}$$

$$S_D = 9.8 \cdot S_A \cdot T^2 \tag{4-3}$$

The region of constant spectral acceleration is defined by spectral acceleration at a period of 0.3 second. The constant spectral velocity region has spectral acceleration proportional to 1/T and is anchored to the spectral acceleration at a period of 1 second. The period, T_{AV}, is based on the intersection of the region of constant spectral acceleration and constant spectral velocity (spectral acceleration proportional to 1/T). The value of T_{AV} varies depending on the values of spectral acceleration that define these two intersecting regions. The constant spectral displacement region has spectral acceleration proportional to $1/T^2$ and is anchored to spectral acceleration at the period, T_{VD}, where constant spectral velocity transitions to constant spectral displacement.

The period, T_{VD}, is based on the reciprocal of the corner frequency, f_c, which is proportional to stress drop and seismic moment. The corner frequency is estimated in Joyner and Boore (1988) as a function of moment magnitude (**M**). Using Joyner and Boore's formulation, the period T_{VD}, in seconds, is expressed in terms of the earthquake's moment magnitude as shown by the following Equation (4-4):

$$T_{VD} = 1/f_c = 10^{\frac{(M-5)}{2}} \tag{4-4}$$

When the moment magnitude of the scenario earthquake is not known (e.g., when using USGS maps or user-supplied maps), the period T_{VD} is assumed to be 10 seconds (i.e., moment magnitude is assumed to be **M** = 7.0).

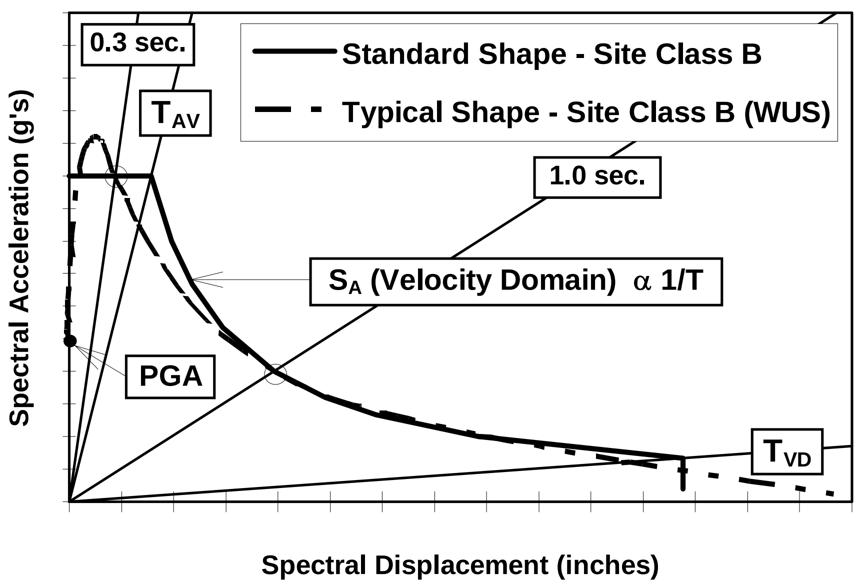


Figure 4.2 Standardized Response Spectrum Shape

Using a standard response spectrum shape simplifies calculation of response needed in estimating damage and loss.

In reality, the shape of the spectrum will vary depending on whether the earthquake occurs in the WUS or CEUS, whether it is a large or moderate size event and whether the site is near or far from the earthquake source. However, the differences between the shape of an actual spectrum and the standard spectrum tend to be significant only at periods less than 0.3 second and at periods greater than T_{VD}, which do not significantly affect the Methodology's estimation of damage and loss.

The standard response spectrum shape (with adjustment for site amplification) represents all site/source conditions, except for site/source conditions that have strong amplification at periods beyond 1 second. Although relatively rare, strong amplification at periods beyond 1 second can occur. For example, strong amplification at a period of about 2 seconds caused extensive damage and loss to taller buildings in parts of Mexico City during the 1985 Michoacan earthquake. In this case, the standard response spectrum shape would tend to overestimate short-period spectral acceleration and to underestimate long-period (i.e., greater than 1-second) spectral acceleration.

Inferred Ground Shaking Hazard Information

Certain ground shaking hazard information is inferred from other ground shaking hazard information when complete hazard data is not available. Inferred data may include the following:

- Peak ground velocity (PGV) is inferred from 1-second spectral acceleration response
- Spectral acceleration response is inferred from the peak ground acceleration (PGA)
- 0.3-second spectral acceleration response is inferred from 0.2-second response

PGV Inferred from 1-Second Spectral Response

Unless supplied by the user (i.e., as user-supplied PGV maps), peak ground velocity (inches per second) is inferred from 1-second spectral acceleration, S_{A1} (units of g), using Equation (4-5).

$$PGV = \left(\frac{386.4}{2\pi} \cdot S_{A1}\right)/1.65 \tag{4-5}$$

The factor of 1.65 in the denominator of Equation (4-5) represents the amplification assumed to exist between peak spectral response and PGV. This factor is based on the median spectrum amplification, as given in Table 2 of Newmark and Hall (1982) for a 5%-damped system whose period is within the velocity-domain region of the response spectrum.

Spectral Acceleration Response Inferred from Peak Ground Acceleration (PGA)

When a user has maps of PGA only, spectral acceleration for the short periods, SA_S, maps are developed from PGA, and spectral acceleration for the long period, SA_L, is inferred from short period spectral acceleration, SA_S, based on the factors given in Table 4.2 for WUS and CEUS rock (Site Class B) locations.

The factors given in Table 4.2 are based on the combination attenuation functions for WUS and CEUS events (Section 4.1.2.3). These factors distinguish between small-magnitude and large-magnitude events and between sites that are located at different distances (i.e. CUES: distance to hypocenter and WUS: distance to fault rupture plane). The ratios of SA_S/SA_L and SA_S/PGA define the standard shape of the response spectrum for each of the magnitude/distance combinations of Table 4.2.

Table 4.2 requires magnitude and distance information to determine spectrum amplification factors. This information would likely be available for maps of observed earthquake PGA, or scenario earthquake PGA, but is not available for probabilistic maps of PGA, since these maps are aggregated estimates of seismic hazard due to different event magnitudes and sources.

Table 4.2 Spectral Acceleration Response Factors

Western United States (WUS) – Rock (Site Class B)								
Distance (km)	**SA_S/PGA given Magnitude, M:**				**SA_S/SA_L given Magnitude, M:**			
	5	**6**	**7**	**7.5**	**5**	**6**	**7**	**7.5**
10 km	1.5	1.8	1.9	1.9	4.5	2.8	1.9	1.6
25 km	1.5	1.8	1.9	1.9	4.8	3.1	2.1	1.8
50 km	1.4	1.8	1.9	1.9	4.5	2.9	2.0	1.7
75 km	1.4	1.8	1.9	1.8	4.3	2.8	1.8	1.6
Central and Eastern United States (CEUS) – Rock (Site Class B)								
10 km	0.8	1.1	1.4	1.7	7.7	4.2	3.0	2.7
25 km	0.9	1.2	1.4	1.5	6.9	4.0	2.9	2.6
50 km	1.0	1.4	1.6	1.7	5.2	3.8	2.7	2.4
75 km	1.2	1.5	1.7	1.8	9.2	3.5	2.6	2.4

0.3-Second Spectral Acceleration Response Inferred from 0.2-Second Response

The factors describing the ratio of 0.2-second and 0.3-second response are based on the default combinations of WUS and CEUS attenuation functions, described in the next section, and the assumption that large-magnitude events tend to dominate seismic hazard at most WUS locations and that small-magnitude events tend to dominate seismic hazard at most CEUS locations.

4.1.2.3 Attenuation of Ground Shaking

Ground shaking is attenuated with distance from the source using relationships provided with the Methodology.

Table 4.3 below lists the 14 ground motion relation proposed for use by Hazus to model ground motions and identifies the applicable region(s), the number of different types of faulting modeled by each relation, and the definition(s) of fault distance parameter used by each relation.

Table 4.3 Summary list of the 14 ground motion relation proposed for use by Hazus to model ground motions and identifies the applicable region(s), the number of different types of faulting modeled by each relation, and the definition(s) of fault distance parameter used by each relation. The three new NGA ground motion relations are indicated by yellow shading.

No.	Ground Motions Relation Modeler(s)	Year	Applicable Seismic Region(s)	Fault Type(s)	Distance Parameter(s)		
					Primary	Other	Other
1	Toro et al.	1997	CEUS, NMSZ and Other	Shallow	R_{JB}		
2	Frankel et al.	1996	CEUS, NMSZ and Other	Shallow	R_{JB}		
3	Campbell	2003	CEUS, NMSZ and Other	Shallow	R_{JB}		
4	Atkinson & Boore	2006	CEUS, NMSZ and Other	Shallow	R_{JB}		
5	Tavakoli & Pezeshk	2005	CEUS, NMSZ and Other	Shallow	R_{JB}		
6	Silva et al.	2002	CEUS, NMSZ and Other	Shallow	R_{JB}		
7	Somerville et al.	2001	NMSZ and Other	Shallow	R_{JB}		
8	Boore & Atkinson	2008	WUS (Shallow Crustal)	SS, RV, NM	R_{JB}		
9	Campbell & Bozorgnia	2008	WUS (Shallow Crustal)	SS, RV, NM	R_{RUP}	R_{JB}	
10	Chiou and Youngs	2008	WUS (Shallow Crustal)	SS, RV, NM	R_{RUP}	R_{JB}	R_X
11	Youngs et al.	1997	Cascadia and Other Deep	IS, IF	R_{RUP}		
12	Atkinson & Boore GM	2003	Cascadia and Other Deep	IS, IF	R_{RUP}		
13	Zhao et al.	2006	Cascadia (Interface)	IF	R_{RUP}		
14	Sadigh et al.	1997	Alaska (Megathrust)	IF	R_{RUP}		

HAZUS look-up tables contain model ground motions for all thes attenuation relations listed in Table 4.3.

Table 4.4 below provides a summary of the combination used to compile the data in look-up tables. For the NGA, these combinations reflect the modeling of ground motions for different widths (W) and dip angles (Dip) of faults in the Hazus (USGS) fault database.

Table 4.4. Summary of the estimated 306 combinations used to populate the look-up tables required for NGA ground motion relations. For tables of hanging wall site ground motions, N_{WD} is the number of unique combinations of different fault width and dip angle required to accurately represent ground motions.

Ground Motion Parameter	Strike Slip Faulting		Reverse Slip/Thrust		Normal Faulting	
	Vertical (Foot Wall)	Hanging Wall Site	Foot Wall Site	Hanging Wall Site	Foot Wall Site	Hanging Wall Site
PGA	3	$(N_{WD})^1 \times 3^4$	3	$(N_{WD})^2 \times 3^4$	3	$(N_{WD})^3 \times 3^4$
SA03	3	$(N_{WD})^1 \times 3^4$	3	$(N_{WD})^2 \times 3^4$	3	$(N_{WD})^3 \times 3^4$
SA10	3	$(N_{WD})^1 \times 3^4$	3	$(N_{WD})^2 \times 3^4$	3	$(N_{WD})^3 \times 3^4$
All	9	$(N_{WD})^1 \times 9^4$	9	$(N_{WD})^2 \times 9^4$	9	$(N_{WD})^3 \times 9^4$

Combination Attenuation Relationships

Tables 4.5 summarizes the 13 combinations of 14 relations proposed for use by Hazus to model ground motions in a manner to that developed by the USGS for the 2008 seismic hazard maps. Note. WUS relations, including the new NGA ground motions, are used for similar faulting in Alaska, Hawaii and Puerto Rico-Virgin Islands in lieu of older relations of these regions..

Table 4.5 Combination Attenuation Relationships

Seismic Region		CEUS		Shallow Crustal Faults						Deep Faults	
Prime	Sub-Region/Class	CEUS	NMSZ	SS (FW)	SS-HW	RV-HW	RV-FW	NM-HW	NM-FW	Interface	In-Slab
CEUS	Unknown Faulting	1									
	Known Faulting		2								
WUS	Coast Californa			3	4	5	6	7	8		
	Extensional			3	4	5	6	7	8		
	Non-Extensional			3	4	5	6	7	8		
	Inter-Mountain West			3	4	5	6	7	8		
	Wasatch			3	4	5	6	7	8		
	Pacific Northwest			3	4	5	6	7	8		
	Cascadia Subduction									9	10
Other	Alaska			3	4	5	6	7	8	9, 11	12
	Hawaii			3	4	5	6	7	8		12
	Puerto Rico-Virgin Isles			3	4	5	6	7	8	9	12
WUS/Other Unknown Faulting				13							12

1. CEUS - (0.25)Toro et al. 97+(0.125)Frankel et al 96+(0.125)Campbell 03+(0.25)AB 06+(0.125)TP 05+(0.125)Silva et al. 02
2. NMSZ - (0.2)Toro 97+(0.1)Frankel 96+(0.1)Campbell 03+(0.2)AB 06+(0.1)TP 05+(0.1)Silva etal.02+(0.2)Somerville etal.01
3. WUS - Strike-Slip (Vertical or Foot Wall) - NGA = (0.33) BA 2008 + (0.33) CB 2008 + (0.33) CY 2008
4. WUS- Strike Slip (Hanging Wall) - NGA Mix = (0.33) BA 2008 + (0.33) CB 2008 + (0.33) CY 2008
5. WUS - Reverse (Hanging Wall) - NGA Mix = (0.33) BA 2008 + (0.33) CB 2008 + (0.33) CY 2008
6. WUS - Reverse (Foot Wall) - NGA Mix = (0.33) BA 2008 + (0.33) CB 2008 + (0.33) CY 2008
7 WUS - Normal (Hanging Wall) - NGA Mix = (0.33) BA 2008 + (0.33) CB 2008 + (0.33) CY 2008
8 WUS - Normal (Foot Wall) - NGA Mix = (0.33) BA 2008 + (0.33) CB 2008 + (0.33) CY 2008
9. Cascadia Subduction Zone - Plate Interface (IT) - (0.25) Youngs et al. 1997 + (0.25) AB 2003,global + (0.5) Zhao et al. 2006
10. Cascadia Subduction Zone - Intraslab - (0.25) Youngs et al. 1997 + (0.25) AB Global 2003 + (0.5) Zhao et al. 2006
11. Megathrust/Interface - (0.5) Sadigh et al., 97 + (0.5) Youngs et al. 97 (IT) Note. PR-VI = (1.0) Youngs et al. 97 at R > 58 km.
12. Deep/Deeper Intraslab - (0.5) Youngs et al. 1997 + (0.5) AB Global 2003. Note. At least two different fault depths.
13. Shallow (non-CEUS) Unknown Faults - NGA Mix assuming (0.5) SS + (0.25) RV-FW + (0.25) RV-HW fault type.

Note that the combination CEUS attenuation function predict significantly stronger ground shaking than the combinations of WUS attenuation functions for the same scenario earthquake (i.e., same moment magnitude, soil type, and distance to source).

4.1.2.4 Source-to-Site Distance Measures for Attenuation Functions

The source-to-site distance is an integral part of each attenuation relationship and characterizes the decrease in ground shaking intensity as the distance from the earthquake source increases. The distance measures used in the Methodology are described in Table 4.7 and illustrated in Figures 4.3 and 4.4. Figure 4.3 illustrates the distance measures from a vertical fault plane while Figure 4.4 illustrates the same measure for a dipping fault. In the Methodology, all distances and fault dimensions are in kilometers.

Table 4.7 Source-to-Site Distance Measures

Distance	Description
R_{EPI}	Distance from the site to the earthquake epicenter
R_{HYPO}	Distance from the site to the earthquake hypocenter
R_{JB}	Distance from the site to the vertical projection of the fault rupture plane
R_{CD}	Closest Distance to the fault
R_{RUP}	Distance from the site to the fault rupture plane
Depth (d)	Distance to Rupture Top Depth (also referred to as ***Ztor*** in NGA models)
R_X	Horizontal distance to top edge of rupture
R_{SEIS}	Distance from the site to the seismogenic portion of the fault rupture plane.

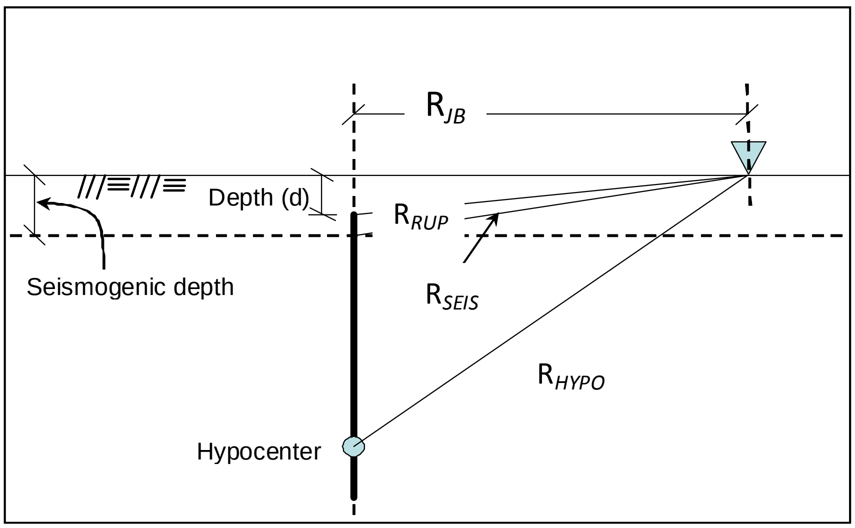


Figure 4.3 Source-to-Site Distances for Vertical Faults

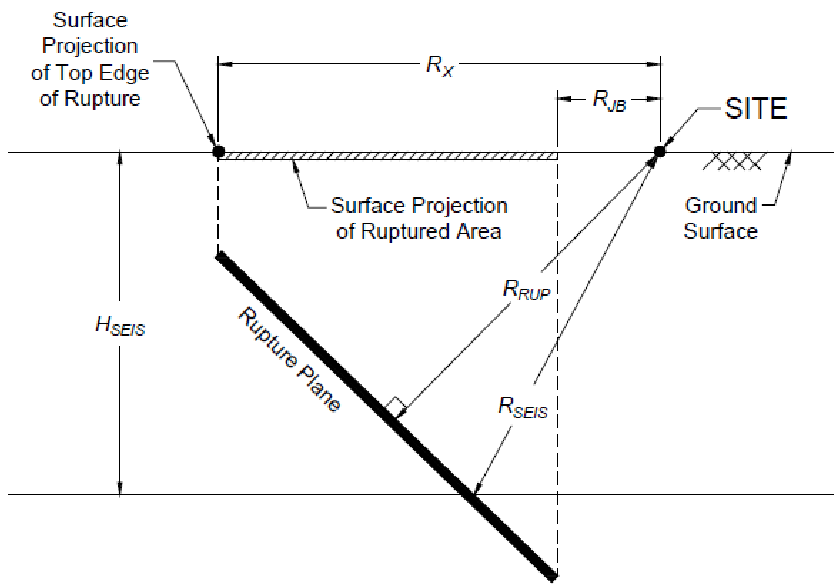


Figure 4.4 Source-to-Site Distances for Dipping Faults.

4.1.2.5 Amplification of Ground Shaking - Local Site Conditions

Amplification of ground shaking to account for local site conditions is based on the site classes and soil amplification factors proposed for the *1997 NEHRP Provisions* (which are essentially the same as the 1994 *NEHRP Provisions,* FEMA 222A, 1995). The *NEHRP Provisions* define a standardized site geology classification scheme and specify soil amplification factors for most site classes. The classification scheme of the NEHRP Provisions is based, in part, on the average shear wave velocity of the upper 30 meters of the local site geology, as shown in Table 4.8. Users (with geotechnical expertise) are required to relate the soil classification scheme of soil maps to the classification scheme shown in Table 4.8.

Table 4.8 Site Classes (from the 1997 *NEHRP Provisions*)

Site Class	Site Class Description	Shear Wave Velocity (m/sec)	
		Minimum	**Maximum**
A	**HARD ROCK** Eastern United States sites only	1500	
B	**ROCK**	760	1500
C	**VERY DENSE SOIL AND SOFT ROCK** Untrained shear strength $u_s \geq 2000$ psf ($u_s \geq 100$ kPa) or $N \geq 50$ blows/ft	360	760
D	**STIFF SOILS** Stiff soil with undrained shear strength 1000 psf $\leq u_s \leq 2000$ psf (50 kPa $\leq u_s \leq$ 100 kPa) or $15 \leq N \leq 50$ blows/ft	180	360
E	**SOFT SOILS** Profile with more than 10 ft (3 m) of soft clay defined as soil with plasticity index PI > 20, moisture content *w* > 40% and undrained shear strength u_s < 1000 psf (50 kPa) (N < 15 blows/ft)		180
F	**SOILS REQUIRING SITE SPECIFIC EVALUATIONS** **1. Soils vulnerable to potential failure or collapse under seismic loading:** e.g. liquefiable soils, quick and highly sensitive clays, collapsible weakly cemented soils. **2. Peats and/or highly organic clays** (10 ft (3 m) or thicker layer) **3. Very high plasticity clays:** (25 ft (8 m) or thicker layer with plasticity index >75) **4. Very thick soft/medium stiff clays:** (120 ft (36 m) or thicker layer)		

Soil amplification factors are provided in Table 4.9 for Site Classes A, B, C, D and E. No amplification factors are available for Site Class F, which requires special site-specific geotechnical evaluation and is not used in the Methodology.

Table 4.9 Soil Amplification Factors

Site Class B Spectral Acceleration	Site Class				
	A	**B**	**C**	**D**	**E**
Short-Period, S_{AS} (g)	**Short-Period Amplification Factor, F_A**				
≤ 0.25	0.8	1.0	1.2	1.6	2.5
0.50	0.8	1.0	1.2	1.4	1.7
0.75	0.8	1.0	1.1	1.2	1.2
1.0	0.8	1.0	1.0	1.1	0.9
≥ 1.25	0.8	1.0	1.0	1.0	0.9
1-Second Period, S_{A1} (g)	**1.0-Second Period Amplification Factor, F_V**				
≤ 0.1	0.8	1.0	1.7	2.4	3.5
0.2	0.8	1.0	1.6	2.0	3.2
0.3	0.8	1.0	1.5	1.8	2.8
0.4	0.8	1.0	1.4	1.6	2.4
≥ 0.5	0.8	1.0	1.3	1.5	2.4

* Site Class E amplification factors are not provided in the *NEHRP Provisions when S_{AS} > 1.0 or S_{A1} > 0.4*. Values shown with an asterisk are based on judgment.

The *NEHRP Provisions* do not provide soil amplification factors for PGA or PGV. The Methodology amplifies rock (Site Class B) PGA by the same factor as that specified in Table 4.10 for short-period (0.3-second) spectral acceleration, as expressed in Equation (4-15), and amplifies rock (Site Class B) PGV by the same factor as that specified in Table 4.10 for 1.0-second spectral acceleration, as expressed in Equations (4-16).

$$PGA_i = PGA \cdot F_{Ai} \tag{4-15}$$

$$PGV_i = PGV \cdot F_{Vi} \tag{4-16}$$

where:

	PGA_i	is peak ground acceleration for Site Class i (in units of g)
	PGA	is peak ground acceleration for Site Class B (in units of g)
	F_{Ai}	is the short-period amplification factor for Site Class i, as specified in Table 4.10 for spectral acceleration, S_{AS}
	PGV_i	is peak ground acceleration for Site Class i (in units of g)
	PGV	is peak ground acceleration for Site Class B (in units of g)
	F_{Vi}	is the 1-second period amplification factor for Site Class i, as specified in Table 4.10 for spectral acceleration, S_{A1}

Construction of Demand Spectra

Demand spectra including soil amplification effects are constructed at short-periods using Equation (4-17) and at long-periods using Equation (4-18). The period, T_{AV}, which defines the transition period from constant spectral acceleration to constant spectral velocity is a function of site class, as given in Equation (4-19). The period, T_{VD}, which defines the transition period from constant spectral velocity to constant spectral displacement is defined by Equation (4-4), and is not a function of site class.

$$S_{ASi} = S_{AS} \cdot F_{Ai} \tag{4-17}$$

$$S_{A1i} = S_{A1} \cdot F_{Vi} \tag{4-18}$$

$$T_{AVi} = \left(\frac{S_{A1}}{S_{AS}}\right)\left(\frac{F_{Vi}}{F_{Ai}}\right) \tag{4-19}$$

where:
- S_{ASi} is short-period spectral acceleration for Site Class i (in units of g)
- S_{AS} is short-period spectral acceleration for Site Class B (in units of g)
- F_{Ai} is the short-period amplification factor for Site Class i, as specified in Table 4.10 for spectral acceleration, S_{AS}
- S_{A1i} is 1-second period spectral acceleration for Site Class i (in units of g)
- S_{A1} is 1-second period spectral acceleration for Site Class B (in units of g)
- F_{Vi} is the 1-second period amplification factor for Site Class i, as specified in Table 4.10 for spectral acceleration, S_{A1}
- T_{AVi} is the transition period between constant spectral acceleration and constant spectral velocity for Site Class i (sec).

Figure 4.5 illustrates construction of response spectra for Site Class D (stiff soil) and E (soft soil) from Site Class B (rock) response spectra. These spectra represent response (of a 5%-damped, linear-elastic single-degree-of-freedom system) located at a WUS site, 20 km from a magnitude **M** = 7.0 earthquake, as predicted by the default combination of WUS attenuation relationships. Figure 4.5 shows the significance of soil type on site response (i.e., increase in site response with decrease in shear wave velocity) and the increase in the value of the transition period, T_{AV}, with decrease in shear wave velocity.

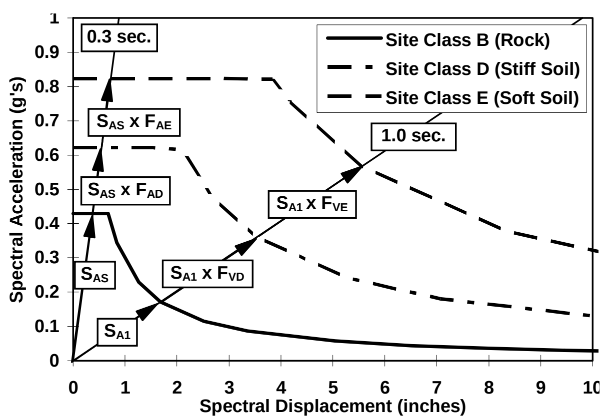


Figure 4.5 Example Construction of Site Class B, C and D Spectra - WUS

4.1.3 Guidance for Expert-Generated Ground Motion Estimation

Ground motion estimation is a sophisticated combination of earth science, engineering and probabilistic methods and should not be attempted by users, including local geotechnical engineers, who not have the proper expertise.

For users who don't have the expertise to estimate ground motion and who need guidance on which existing attenuation function to use, the table below summarizes the 59 choices that currently exist within HAZUS. Note that the dependent attenuation functions are the cocktail-based ones in HAZUS.

Attenuation Function #	Description	Fault Mechanism	East or West US	Note
1	Toro et al. (1997)	E	E	
2	Frankel (1996)	E	E	
3	Campbell (2003)	E	E	
4	Atkinson and Boore (2006)	E	E	
5	Tavakoli_Pezeshk (2005)	E	E	
6	Silva et al (2002)	E	E	
7	Somerville (2002)	E	E	
8	NGA - Boore & Atkinson (2008) - Strike Slip	S	W	
9	NGA - Boore & Atkinson (2008) - Reverse	R	W	
10	NGA - Boore & Atkinson (2008) - Normal	N	W	
11	NGA - Chiou & Youngs (2008) - Strike Slip	S	W	
12	NGA - Chiou & Youngs (2008) - Reverse	R	W	
13	NGA - Chiou & Youngs (2008) - Normal	N	W	
14	NGA - Campbell & Bozorgnia (2008) - Strike Slip	S	W	
15	NGA - Campbell & Bozorgnia (2008) - Reverse	R	W	
16	NGA - Campbell & Bozorgnia (2008) - Normal	N	W	
17	NGA - Abrahamson & Silva (2008) - Strike Slip	S	W	
18	NGA - Abrahamson & Silva (2008) - Reverse	R	W	
19	NGA - Abrahamson & Silva (2008) - Normal	N	W	
20	Cascadia - Youngs et al. (1997) - Interslab	F	W	
21	Cascadia - Youngs et al. (1997) - Interface	I	W	
22	Atkinson & Boore, Global (2002) - Interslab	F	W	
23	Atkinson & Boore, Global (2002) - Interface	I	W	
24	Atkinson & Boore (2002), Regional -Interslab	F	W	
25	Atkinson & Boore (2002), Regional -Interface	I	W	
26	Zhao and Others (2006) - Interslab	F	W	
27	Zhao and Others (2006) - Interface	I	W	
28	Central & East US (CEUS 2008)	E	E	Dependent
29	CEUS, New Madrid Seismic Zone (NMSZ 2008)	E	E	Dependent
30	CEUS, Charleston 2008	E	E	Dependent
31	West US, Coastal California 2008 - Strike Slip	S	W	Dependent
32	West US, Coastal California 2008 - Reverse	R	W	Dependent
33	West US, Coastal California 2008 - Normal	N	W	Dependent
34	West US, Extensional 2008 - Strike Slip	S	W	Dependent
35	West US, Extensional 2008 - Reverse	R	W	Dependent
36	West US, Extensional 2008 - Normal	N	W	Dependent
37	West US, Non-Extensional 2008 - Strike Slip	S	W	Dependent
38	West US, Non-Extensional 2008 - Reverse	R	W	Dependent
39	West US, Non-Extensional 2008 - Normal	N	W	Dependent
40	West US, inter-Mountain West - Strike Slip	S	W	Dependent
41	West US, inter-Mountain West - Reverse	R	W	Dependent
42	West US, inter-Mountain West - Normal	N	W	Dependent
43	West US, Wasatch 2008 - Strike Slip	S	W	Dependent
44	West US, Wasatch 2008 - Reverse	R	W	Dependent
45	West US, Wasatch 2008 - Normal	N	W	Dependent
46	Pacific Northwest (PNW 2008) - Strike Slip	S	W	Dependent
47	Pacific Northwest (PNW 2008) - Reverse	R	W	Dependent
48	Pacific Northwest (PNW 2008) - Normal	N	W	Dependent
49	Cascadia - Subduction / Interface (2008)	F	W	Dependent
50	Cascadia - Subduction / Interslab (2008)	I	W	Dependent
51	Alaska or Puerto Rico / VI - Strike Slip	S	W	Dependent
52	Alaska or Puerto Rico / VI - Reverse	R	W	Dependent
53	Alaska or Puerto Rico / VI - Normal	N	W	Dependent
54	Alaska or Puerto Rico / VI - Subduction / Interslab	F	W	Dependent
55	Alaska or Puerto Rico / VI - Subduction / Interface	I	W	Dependent
56	Hawaii - Reverse	R	W	Dependent
57	Hawaii - Volcanic/Shallow	N	W	Dependent
58	Hawaii - Volcanic/Deep	N	W	Dependent
59	Hawaii - Munson and Thurber (1997)	N	W	

When the user creates a study region, HAZUS will recognize whether this region is the east coast (E) or west-coast (W), and automatically filters from the table above the ones applicable for that region.

The dependent (cocktail-based) attenuations are what would show up as a default in HAZUS. However, the user can choose a more specific attenuation for a variety of reasons that include the following:

- Understanding the effects of different attenuation functions on the results. This is in particular very important given that ground motion has the maximum impact possible on the results.

- Simulating and setting up upper bound and lower bound estimates due to ground motion. In this case, the user needs to know which of the attenuation functions provide the smallest shaking and which of the attenuation functions provide the largest shaking.

- Similar comparisons of ground motion should be done for study regions in the western US. When a user wants to choose a particular attenuation function he/she needs to consider the distance between the source and the community/study region for which upper and lower bound losses need to be determined.

4.2 Ground Failure
4.2.1 Introduction

Three types of ground failure are considered: liquefaction, landsliding and surface fault rupture. Each of these types of ground failure is quantified by permanent ground deformation (PGD). Methods and alternatives for determining PGD due to each mode of ground failure are discussed below.

4.2.1.1 Scope

The scope of this section is to provide methods for evaluating the ground failure hazards of: (a) liquefaction, (b) landsliding, and (c) surface fault rupture. The evaluation of the hazard includes the probability of the hazard occurring and the resulting ground displacement.

4.2.1.2 Input Requirements and Output Information

<u>Input</u>
Liquefaction
- A geologic map based on the age, depositional environment, and possibly the material characteristics of the geologic units will be used with Table 4.10 to create a liquefaction susceptibility map
- Groundwater depth map is supplied with a default depth of 5 feet.
- Earthquake Moment Magnitude (**M**)

Landsliding
- A geologic map, a topographic map, and a map with ground water conditions will be used with Table 4.15 to produce a landslide susceptibility map
- Earthquake Moment Magnitude (**M**)

Surface Fault Rupture
- Location of the surface trace of a segment of an active fault that is postulated to rupture during the scenario earthquake

<u>Output</u>
Liquefaction and Landsliding
- Aerial depiction map depicting estimated permanent ground deformations.

Surface Fault Rupture
- No maps are generated, only site-specific demands are determined.

4.2.2 Description of Methods

4.2.2.1 Liquefaction

4.2.2.1.1 Background

Liquefaction is a soil behavior phenomenon in which a saturated soil looses a substantial amount of strength due to high excess pore-water pressure generated by and accumulated during strong earthquake ground shaking.

Youd and Perkins (1978) have addressed the liquefaction susceptibility of various types of soil deposits by assigning a qualitative susceptibility rating based upon general depositional environment and geologic age of the deposit. The relative susceptibility ratings of Youd and Perkins (1978) shown in Table 4.10 indicate that recently deposited relatively unconsolidated soils such as Holocene-age river channel, flood plain, and delta deposits and uncompacted artificial fills located below the groundwater table have high to very high liquefaction susceptibility. Sands and silty sands are particularly susceptible to liquefaction. Silts and gravels also are susceptible to liquefaction, and some sensitive clays have exhibited liquefaction-type strength losses (Updike, et. al., 1988).

Permanent ground displacements due to lateral spreads or flow slides and differential settlement are commonly considered significant potential hazards associated with liquefaction.

4.2.2.1.2 Liquefaction Susceptibility

The initial step of the liquefaction hazard evaluation is to characterize the relative liquefaction susceptibility of the soil/geologic conditions of a region or subregion. Susceptibility is characterized utilizing geologic map information and the classification system presented by Youd and Perkins (1978) as summarized in Table 4.10. Large-scale (e.g., 1:24,000 or greater) or smaller-scale (e.g., 1:250,000) geologic maps are generally available for many areas from geologists at regional U.S. Geological Survey offices, state geological agencies, or local government agencies. The geologic maps typically identify the age, depositional environment, and material type for a particular mapped geologic unit. Based on these characteristics, a relative liquefaction susceptibility rating (e.g., very low to very high) is assigned from Table 4.10 to each soil type. Mapped areas of geologic materials characterized as rock or rock-like are considered for the analysis to present no liquefaction hazard.

Table 4.10 Liquefaction Susceptibility of Sedimentary Deposits (from Youd and Perkins, 1978)

Type of Deposit	General Distribution of Cohesionless Sediments in Deposits	Likelihood that Cohesionless Sediments when Saturated would be Susceptible to Liquefaction (by Age of Deposit)			
		< 500 yr Modern	Holocene < 11 ka	Pleistocene 11 ka - 2 Ma	Pre-Pleistocene > 2 Ma
(a) Continental Deposits					
River channel	Locally variable	Very High	High	Low	Very Low
Flood plain	Locally variable	High	Moderate	Low	Very Low
Alluvial fan and plain	Widespread	Moderate	Low	Low	Very Low
Marine terraces and plains	Widespread	---	Low	Very Low	Very Low
Delta and fan-delta	Widespread	High	Moderate	Low	Very Low
Lacustrine and playa	Variable	High	Moderate	Low	Very Low
Colluvium	Variable	High	Moderate	Low	Very Low
Talus	Widespread	Low	Low	Very Low	Very Low
Dunes	Widespread	High	Moderate	Low	Very Low
Loess	Variable	High	High	High	Unknown
Glacial till	Variable	Low	Low	Very Low	Very Low
Tuff	Rare	Low	Low	Very Low	Very Low
Tephra	Widespread	High	High	?	?
Residual soils	Rare	Low	Low	Very Low	Very Low
Sebka	Locally variable	High	Moderate	Low	Very Low
(b) Coastal Zone					
Delta	Widespread	Very High	High	Low	Very Low
Esturine	Locally variable	High	Moderate	Low	Very Low
Beach					
High Wave Energy	Widespread	Moderate	Low	Very Low	Very Low
Low Wave Energy	Widespread	High	Moderate	Low	Very Low
Lagoonal	Locally variable	High	Moderate	Low	Very Low
Fore shore	Locally variable	High	Moderate	Low	Very Low
(c) Artificial					
Uncompacted Fill	Variable	Very High	---	---	---
Compacted Fill	Variable	Low	---	---	---

Liquefaction susceptibility maps produced for certain regions [e.g., greater San Francisco region (ABAG, 1980); San Diego (Power, et. al., 1982); Los Angeles (Tinsley, et. al., 1985); San Jose (Power, et. al., 1991); Seattle (Grant, et. al., 1991); among others] are also available and may alternatively be utilized in the hazard analysis.

4.2.2.1.3 Probability of Liquefaction

The likelihood of experiencing liquefaction at a specific location is primarily influenced by the susceptibility of the soil, the amplitude and duration of ground shaking and the depth of groundwater. The relative susceptibility of soils within a particular geologic unit is assigned as previously discussed. It is recognized that in reality, natural geologic deposits as well as man-placed fills encompass a range of liquefaction susceptibilities due to variations of soil type (i.e., grain size distribution), relative density, etc. Therefore, portions of a geologic map unit may not be susceptible to liquefaction, and this should be considered in assessing the probability of liquefaction at any given location within the unit. In general, we expect non-susceptible portions to be smaller for higher susceptibilities. This "reality" is incorporated by a probability factor that quantifies the proportion of a geologic map unit deemed susceptible to liquefaction (i.e., the likelihood of susceptible conditions existing at any given location within the unit). For the various susceptibility categories, suggested default values are provided in Table 4.11.

Table 4.11 Proportion of Map Unit Susceptible to Liquefaction

Mapped Relative Susceptibility	Proportion of Map Unit
Very High	0.25
High	0.20
Moderate	0.10
Low	0.05
Very Low	0.02
None	0.00

These values reflect judgments developed based on preliminary examination of soil properties data sets compiled for geologic map units characterized for various regional liquefaction studies (e.g., Power, et. al., 1982).

As previously stated, the likelihood of liquefaction is significantly influenced by ground shaking amplitude (i.e., peak horizontal acceleration, PGA), ground shaking duration as reflected by earthquake magnitude, **M**, and groundwater depth. Thus, the probability of liquefaction for a given susceptibility category can be determined by the following relationship:

$$P\left[\text{Liquefaction}_{SC}\right] = \frac{P\left[\text{Liquefaction}_{SC} \middle| PGA = a\right]}{K_M \cdot K_w} \cdot P_{ml} \qquad (4\text{-}20)$$

where

$P\left[\text{Liquefaction}_{SC} \middle| PGA = a\right]$ is the conditional liquefaction probability for a given susceptibility category at a specified level of peak ground acceleration (See Figure 4.8)

K_M is the moment magnitude (**M**) correction factor (Equation 4-21)

K_w is the ground water correction factor (Equation 4-22)

P_{ml} proportion of map unit susceptible to liquefaction (Table 4.11)

Relationships between liquefaction probability and peak horizontal ground acceleration (PGA) are defined for the given susceptibility categories in Table 4.12 and also represented graphically in Figure 4.6. These relationships have been defined based on the state-of-practice empirical procedures, as well as the statistical modeling of the empirical liquefaction catalog presented by Liao, et. al. (1988) for representative penetration resistance characteristics of soils within each susceptibility category (See Section 4.2.3.2.3) as gleaned from regional liquefaction studies cited previously. Note that the relationships given in Figure 4.6 are simplified representations of the relationships that would be obtained using Liao, et al. (1988) or empirical procedures.

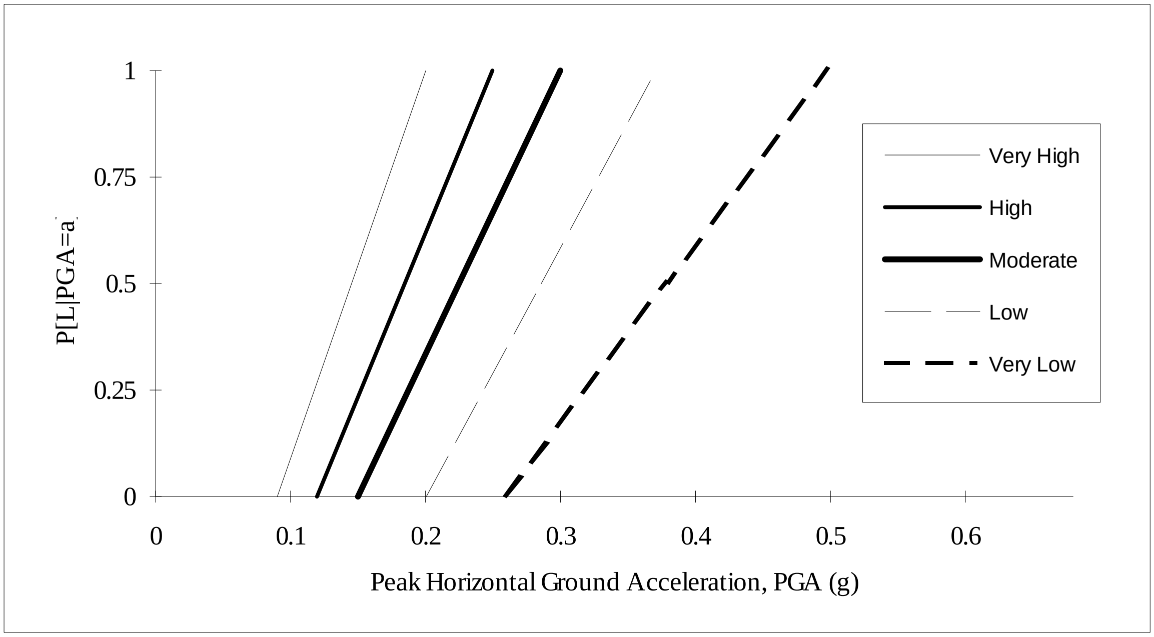


Figure 4.6 Conditional Liquefaction Probability Relationships for Liquefaction Susceptibility Categories (after Liao, et. al., 1988).

Table 4.12 Conditional Probability Relationship for Liquefaction Susceptibility Categories

Susceptibility Category	**P [Liquefaction |PGA = a]**
Very High	$0 \le 9.09\text{ a} - 0.82 \le 1.0$
High	$0 \le 7.67\text{a} - 0.92 \le 1.0$
Moderate	$0 \le 6.67\text{a} -1.0 \le 1.0$
Low	$0 \le 5.57\text{a} -1.18 \le 1.0$
Very Low	$0 \le 4.16\text{a} - 1.08 \le 1.0$
None	0.0

The conditional liquefaction probability relationships presented in Figure 4.6 were developed for a **M** =7.5 earthquake and an assumed groundwater depth of five feet Correction factors to account for other moment magnitudes (**M**) and groundwater depths are given by Equations 4-21 and 4-22 respectively. These modification factors are well recognized and have been explicitly incorporated in state-of-practice empirical procedures for evaluating the liquefaction potential (Seed and Idriss, 1982; Seed, et. al., 1985; National Research Council, 1985). These relationships are also presented graphically in Figures 4.7 and 4.8. The magnitude and groundwater depth corrections are made automatically in the methodology. The modification factors can be computed using the following relationships:

$$K_m = 0.0027\mathbf{M}^3 - 0.0267\mathbf{M}^2 - 0.2055\mathbf{M} + 2.9188 \qquad (4\text{-}21)$$

$$K_w = 0.022d_w + 0.93 \qquad (4\text{-}22)$$

where: K_m is the correction factor for moment magnitudes other than M=7.5;
K_w is the correction factor for groundwater depths other than five feet;
M represents the magnitude of the seismic event, and;
d_w represents the depth to the groundwater in feet.

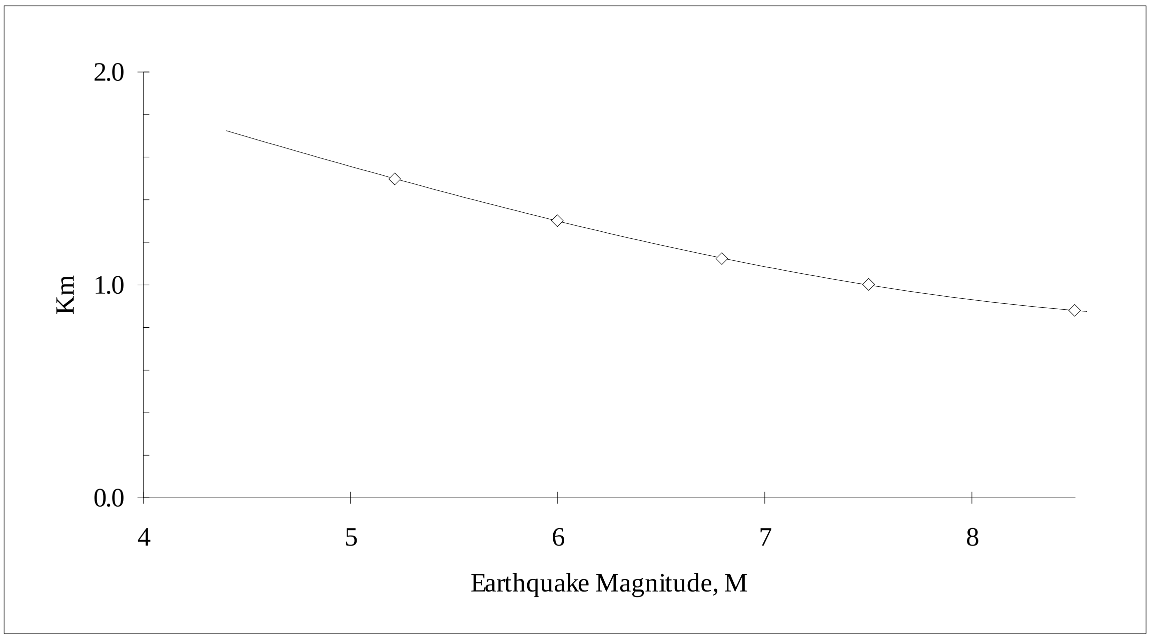


Figure 4.7 Moment Magnitude (M) Correction Factor for Liquefaction Probability Relationships (after Seed and Idriss, 1982).

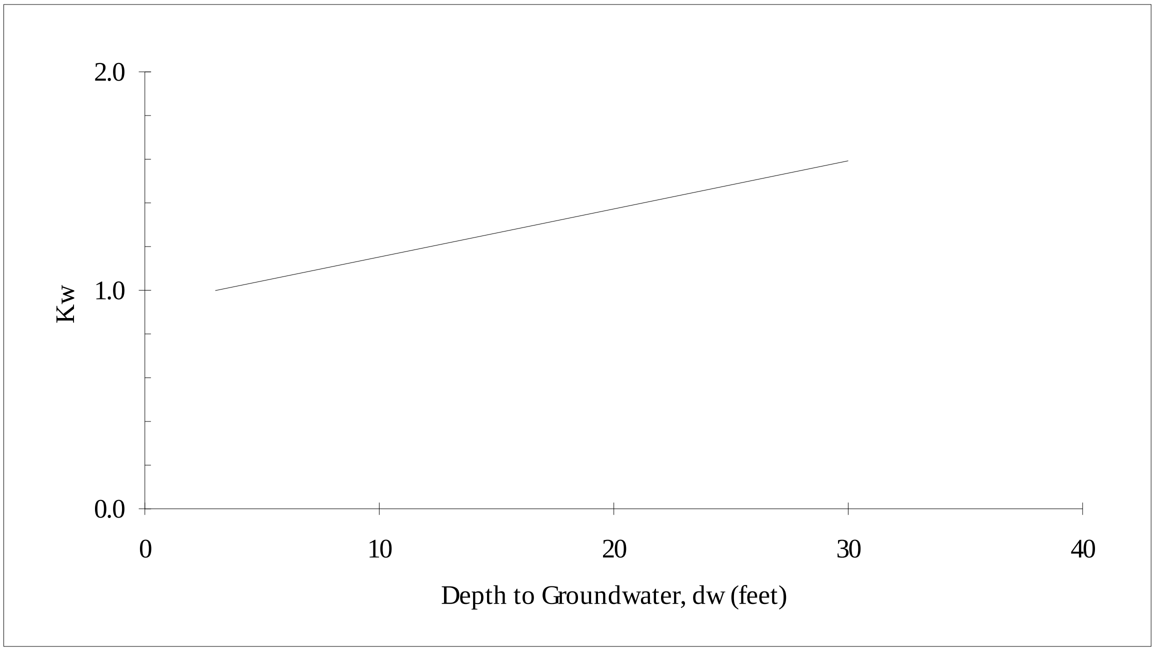


Figure 4.8 Ground Water Depth Correction Factor for Liquefaction Probability Relationships.

4.2.2.1.4 Permanent Ground Displacements

Lateral Spreading

The expected permanent ground displacements due to lateral spreading can be determined using the following relationship:

$$E\left[PGD_{SC}\right] = K_{\Delta} \cdot E\left[PGD \middle| \left(PGA / PL_{SC}\right) = a\right] \quad (4\text{-}23)$$

where

$E\left[PGD \middle| \left(PGA / PL_{SC}\right) = a\right]$	is the expected permanent ground displacement for a given susceptibility category under a specified level of normalized ground shaking (PGA/PGA(t)) (Figure 4.9)
PGA(t)	is the threshold ground acceleration necessary to induce liquefaction (Table 4.13)
K_{Δ}	is the displacement correction factor given by Equation 4-24

This relationship for lateral spreading was developed by combining the Liquefaction Severity Index (LSI) relationship presented by Youd and Perkins (1987) with the ground motion attenuation relationship developed by Sadigh, et. al. (1986) as presented in Joyner and Boore (1988). The ground shaking level in Figure 4.9 has been normalized by the threshold peak ground acceleration PGA(t) corresponding to zero probability of liquefaction for each susceptibility category as shown on Figure 4.6. The PGA(t) values for different susceptibility categories are summarized in Table 4.13.

The displacement term, $E\left[PGD\middle|\left(PGA / PL_{SC}\right) = \mathrm{a}\right]$, in Equation 4-23 is based on **M** = 7.5 earthquakes. Displacements for other magnitudes are determined by modifying this displacement term by the displacement correction factor given by Equation 4-24. This equation is based on work done by Seed & Idriss (1982). The displacement correction factor, K_Δ, is shown graphically in Figure 4.10.

$$K_\Delta = 0.0086\mathbf{M}^3 - 0.0914\mathbf{M}^2 + 0.4698\mathbf{M} - 0.9835 \qquad (4\text{-}24)$$

where **M** is moment magnitude.

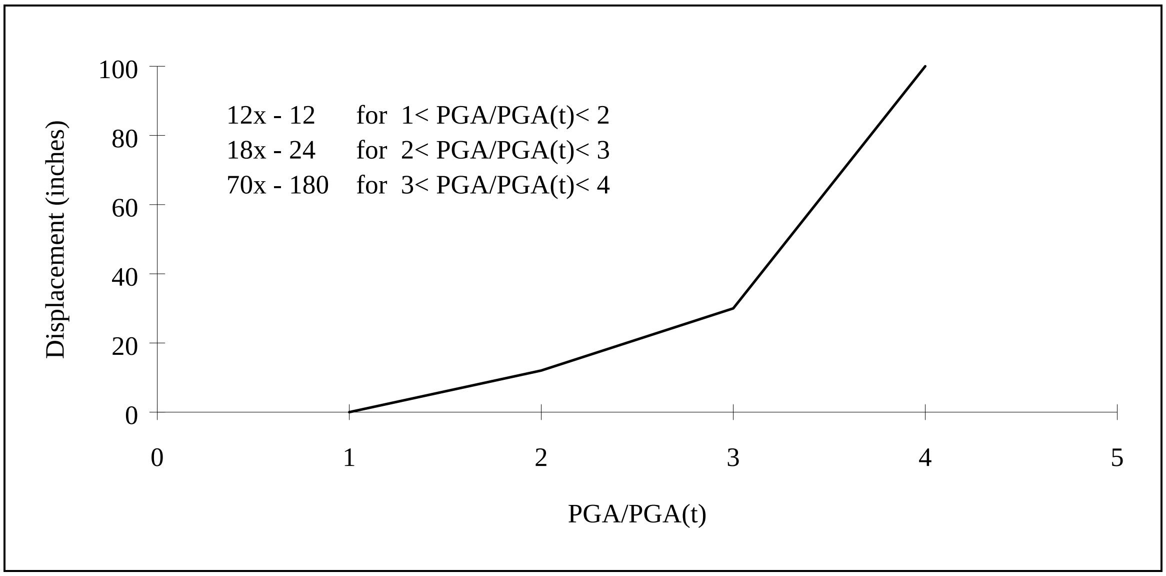


Figure 4.9 Lateral Spreading Displacement Relationship (after Youd and Perkins, 1978; Sadigh, et. al., 1986).

Table 4.13 Threshold Ground Acceleration (PGA(t)) Corresponding to Zero Probability of Liquefaction

Susceptibility Category	PGA(t)
Very High	0.09g
High	0.12g
Moderate	0.15g
Low	0.21g
Very Low	0.26g
None	N/A

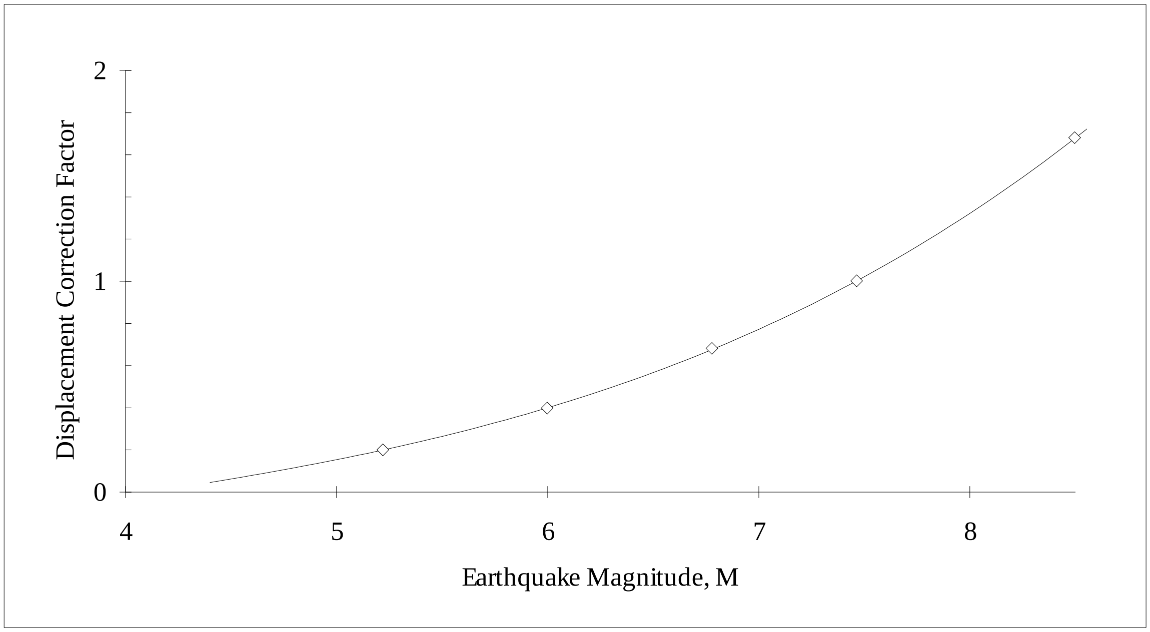


Figure 4.10 Displacement Correction Factor, K_{Δ}, for Lateral Spreading Displacement Relationships (after Seed & Idriss, 1982).

Ground Settlement

Ground settlement associated with liquefaction is assumed to be related to the susceptibility category assigned to an area. This assumption is consistent with relationship presented by Tokimatsu and Seed (1987) that indicate strong correlations between volumetric strain (settlement) and soil relative density (a measure of susceptibility). Additionally, experience has shown that deposits of higher susceptibility tend to have increased thicknesses of potentially liquefiable soils. Based on these considerations, the ground settlement amplitudes are given in Table 4.14 for the portion of a soil deposit estimated to experience liquefaction at a given ground motion level. The uncertainty associated with these settlement values is assumed to have a uniform probability distribution within bounds of one-half to two times the respective value. It is noted that the relationship presented by Tokimatsu and Seed (1987) demonstrate very little dependence of settlement on ground motion level given the occurrence of liquefaction. The expected settlement at a location, therefore, is the product of the probability of liquefaction (Equation 4-18) for a given ground motion level and the characteristic settlement amplitude appropriate to the susceptibility category (Table 4.14).

Table 4.14 Ground Settlement Amplitudes for Liquefaction Susceptibility Categories

Relative Susceptibility	Settlement (inches)
Very High	12
High	6
Moderate	2
Low	1
Very Low	0
None	0

4.2.2.2 Landslide

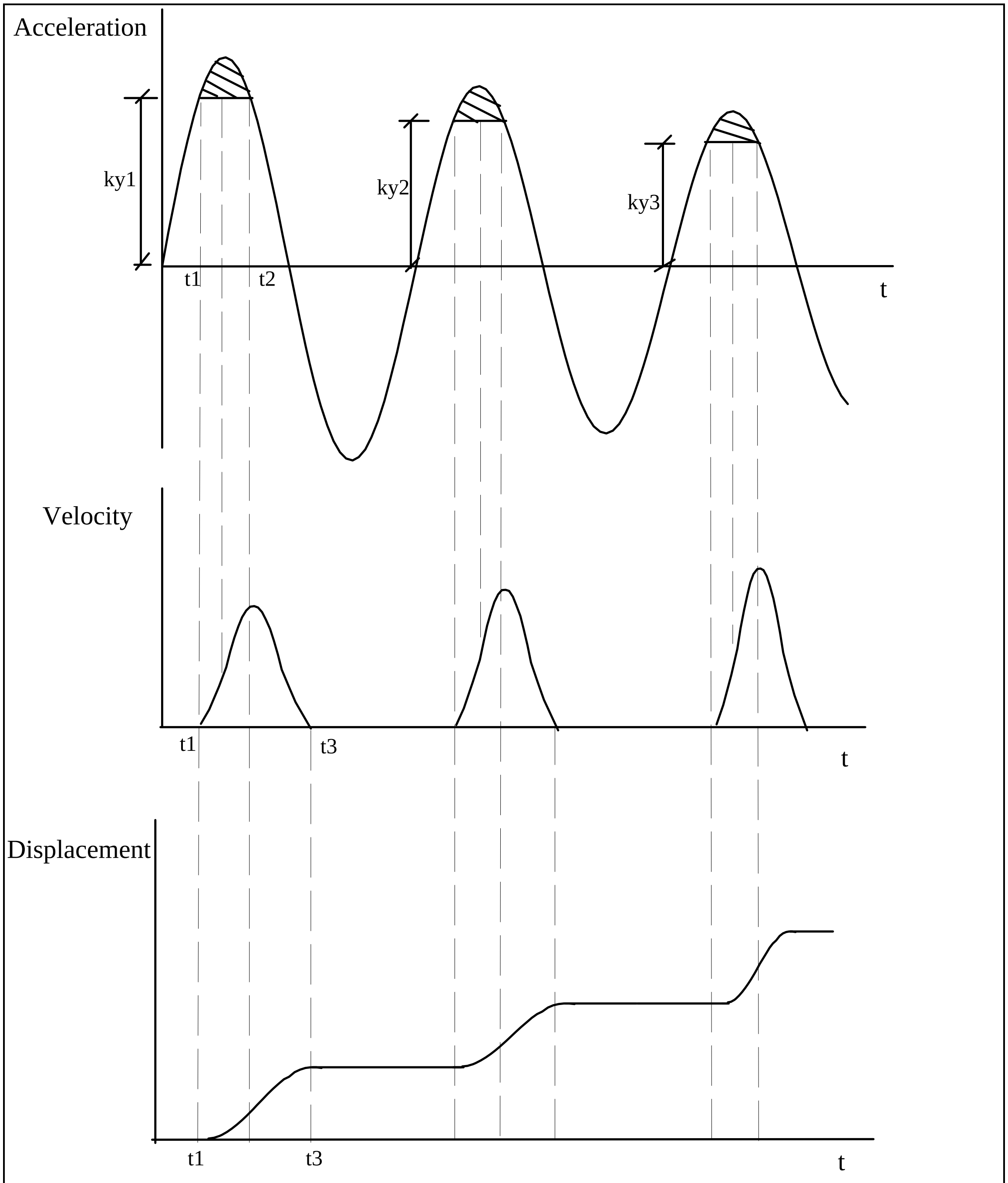
4.2.2.2.1 Background

Earthquake-induced landsliding of a hillside slope occurs when the static plus inertia forces within the slide mass cause the factor of safety to temporarily drop below 1.0. The value of the peak ground acceleration within the slide mass required to just cause the factor of safety to drop to 1.0 is denoted by the critical or yield acceleration a_c. This value of acceleration is determined based on pseudo-static slope stability analyses and/or empirically based on observations of slope behavior during past earthquakes.

Deformations are calculated using the approach originally developed by Newmark (1965). The sliding mass is assumed to be a rigid block. Downslope deformations occur during the time periods when the induced peak ground acceleration within the slide mass a_{is} exceeds the critical acceleration a_c. The accumulation of displacement is illustrated in Figure 4.11. In general, the smaller the ratio (below 1.0) of a_c to a_{is}, the greater is the number and duration of times when downslope movement occurs, and thus the greater is the total amount of downslope movement. The amount of downslope movement also depends on the duration or number of cycles of ground shaking. Since duration and number of cycles increase with earthquake magnitude, deformation tends to increase with increasing magnitude for given values of a_c and a_{is}.

4.2.2.2.2 Landslide Susceptibility

The landslide hazard evaluation requires the characterization of the landslide susceptibility of the soil/geologic conditions of a region or subregion. Susceptibility is



Note: Critical accelerations in figure are ky1, ky2 and ky3. In applications, critical acceleration is usually taken as a single value.

Figure 4.11 Integration of Accelerograms to Determine Downslope Displacements (Goodman and Seed, 1966).

characterized by the geologic group, slope angle and critical acceleration. The acceleration required to initiate slope movement is a complex function of slope geology, steepness, groundwater conditions, type of landsliding and history of previous slope performance. At the present time, a generally accepted relationship or simplified methodology for estimating a_c has not been developed.

The relationship proposed by Wilson and Keefer (1985) is utilized in the methodology. This relationship is shown in Figure 4.12. Landslide susceptibility is measured on a scale of I to X, with I being the least susceptible. The site condition is identified using three geologic groups and groundwater level. The description for each geologic group and its associated susceptibility is given in Table 4.15. The groundwater condition is divided into either dry condition (groundwater below level of the sliding) or wet condition (groundwater level at ground surface). The critical acceleration is then estimated for the respective geologic and groundwater conditions and the slope angle. To avoid calculating the occurrence of landsliding for very low or zero slope angles and critical accelerations, lower bounds for slope angles and critical accelerations are established. These bounds are shown in Table 4.16. Figure 4.12 shows the Wilson and Keefer relationships within these bounds.

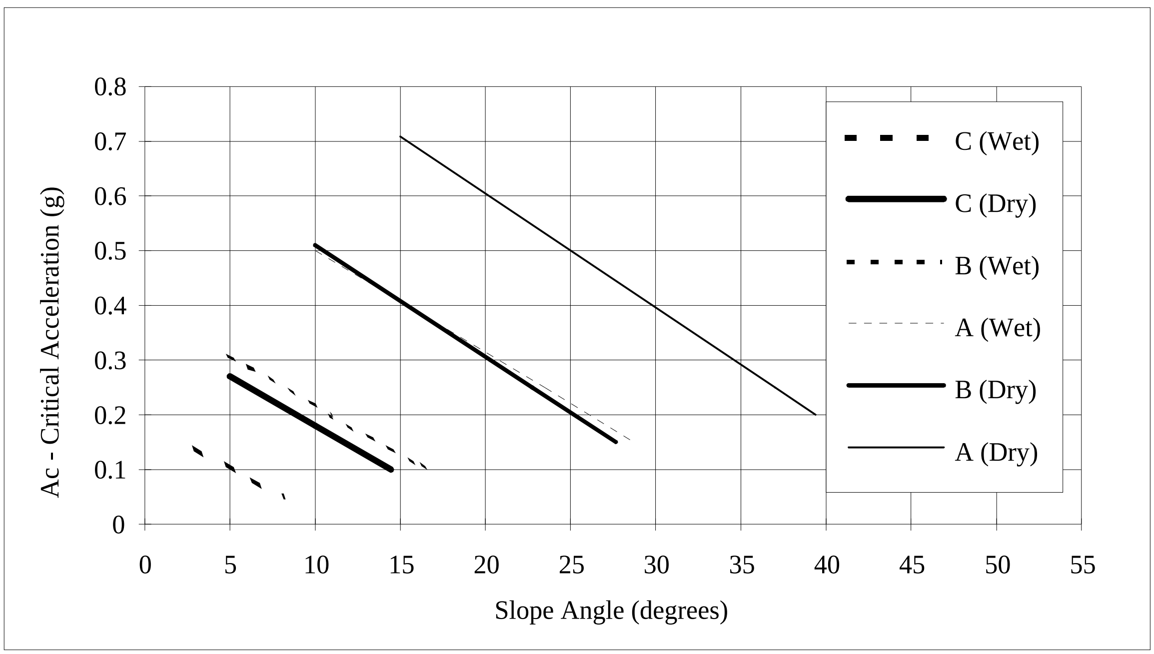


Figure 4.12 Critical Acceleration as a Function of Geologic Group and Slope Angle (Wilson and Keefer, 1985).

Table 4.15 Landslide Susceptibility of Geologic Groups

Geologic Group		Slope Angle, degrees					
		0-10	10-15	15-20	20-30	30-40	>40
(a) DRY (groundwater below level of sliding)							
A	**Strongly Cemented Rocks (crystalline rocks and well-cemented sandstone, $c' = 300$ psf, $\phi' = 35^o$)**	None	None	I	II	IV	VI
B	**Weakly Cemented Rocks and Soils (sandy soils and poorly cemented sandstone, $c' = 0$, $\phi' = 35^o$)**	None	III	IV	V	VI	VII
C	**Argillaceous Rocks (shales, clayey soil, existing landslides, poorly compacted fills, $c' = 0$ $\phi' = 20^o$)**	V	VI	VII	IX	IX	IX
(b) WET (groundwater level at ground surface)							
A	**Strongly Cemented Rocks (crystalline rocks and well-cemented sandstone, $c' = 300$ psf, $\phi' = 35^o$)**	None	III	VI	VII	VIII	VIII
B	**Weakly Cemented Rocks and Soils (sandy soils and poorly cemented sandstone, $c' = 0$, $\phi' = 35^o$)**	V	VIII	IX	IX	IX	X
C	**Argillaceous Rocks (shales, clayey soil, existing landslides, poorly compacted fills, $c' = 0$ $\phi' = 20^o$)**	VII	IX	X	X	X	X

Table 4.16 Lower Bounds for Slope Angles and Critical Accelerations for Landsliding Susceptibility

	Slope Angle, degrees		Critical Acceleration (g)	
Group	**Dry Conditions**	**Wet Conditions**	**Dry Conditions**	**Wet Conditions**
A	15	10	0.20	0.15
B	10	5	0.15	0.10
C	5	3	0.10	0.05

As pointed out by Wieczorek et al. (1985), the relationships in Figure 4.12 are conservative representing the most landslide-susceptible geologic types likely to be found in the geologic group. Thus, in using this relationship further consideration must be given to evaluating the probability of slope failure as discussed in Section 4.2.2.2.3.

In Table 4.17, landslide susceptibility categories are defined as a function of critical acceleration. Then, using Wilson and Keefer's relationship in Figure 4.14 and the lower bound values in Table 4.16, the susceptibility categories are assigned as a function of geologic group, groundwater conditions, and slope angle in Table 4.15. Tables 4.15 and 4.17 thus define the landslide susceptibility.

Table 4.17 Critical Accelerations (a_c) for Susceptibility Categories

Susceptibility Category	None	I	II	III	IV	V	VI	VII	VIII	IX	X
Critical Accelerations (g)	None	0.60	0.50	0.40	0.35	0.30	0.25	0.20	0.15	0.10	0.05

4.2.2.2.3 Probability of Having a Landslide-Susceptible Deposit

Because of the conservative nature of the Wilson and Keefer (1985) correlation, an assessment is made of the percentage of a landslide susceptibility category that is expected to be susceptible to landslide. Based on Wieczorek et al. (1985), this percentage is selected from Table 4.18 as a function of the susceptibility categories. Thus, at any given location, there is a specified probability of having a landslide-susceptible deposit, and landsliding either occurs or does not occur within susceptible deposits depending on whether the induced peak ground acceleration a_{is} exceeds the critical acceleration a_c.

Table 4.18 Percentage of Map Area Having a Landslide-Susceptible Deposit

Susceptibility Category	None	I	II	III	IV	V	VI	VII	VIII	IX	X
Map Area	0.00	0.01	0.02	0.03	0.05	0.08	0.10	0.15	0.20	0.25	0.30

4.2.2.2.4 Permanent Ground Displacements

The permanent ground displacements are determined using the following expression:

$$E[PGD] = E\left[d / a_{is}\right] \cdot a_{is} \cdot n \tag{4-25}$$

where

$E\left[d / a_{is}\right]$ is the expected displacement factor (Figure 4.14)
a_{is} is the induced acceleration (in decimal fraction of g's)
n is the number of cycles (Equation 4-26).

A relationship between number of cycles and earthquake moment magnitude (**M**) based on Seed and Idriss (1982) is shown in Figure 4.13 and can be expressed as follows.

$$n = 0.3419\mathbf{M}^3 - 5.5214\mathbf{M}^2 + 33.6154\mathbf{M} - 70.7692 \tag{4-26}$$

The induced peak ground acceleration within the slide mass, a_{is}, represents the average peak acceleration within the entire slide mass. For relatively shallow and laterally small slides, a_{is} is not significantly different than the induced peak ground surface acceleration

a_i. For deep and large slide masses a_{is} is less than a_i. For many applications a_{is} may be assumed equal to the accelerations predicted by the peak ground acceleration attenuation relationships being used for the loss estimation study. Considering also that topographic amplification of ground motion may also occur on hillside slopes (which is not explicitly incorporated in the attenuation relationships), the assumption of a_{is} equal to a_i may be prudent. The user may specify a ratio a_{is}/a_i less than 1.0. The default value is 1.0.

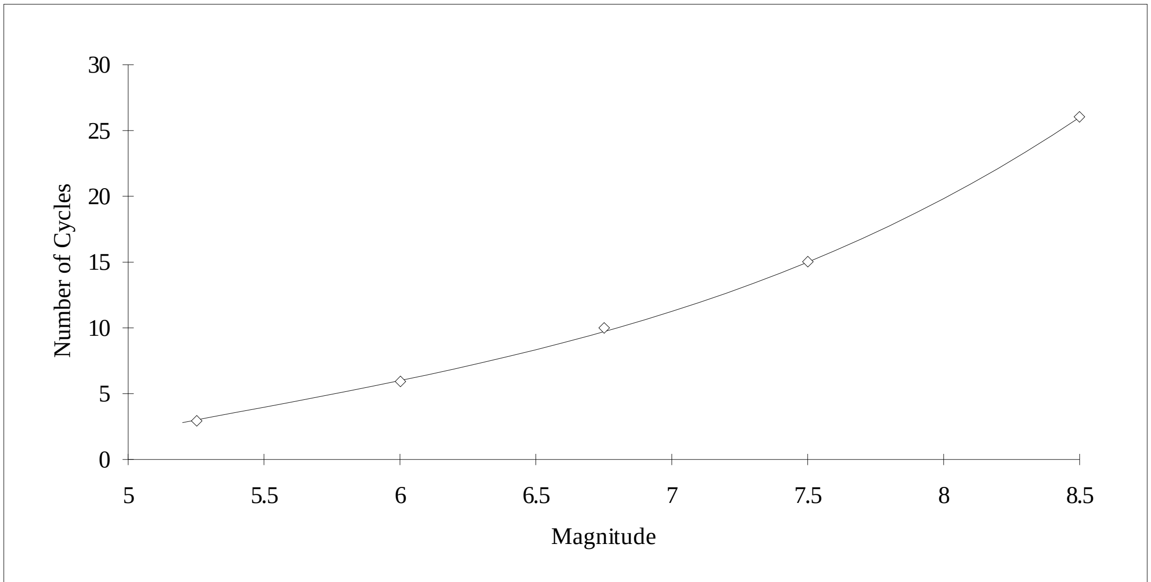


Figure 4.13 Relationship between Earthquake Moment Magnitude and Number of Cycles.

A relationship derived from the results of Makdisi and Seed (1978) is used to calculate downslope displacements. In this relationship, shown in Figure 4.14, the displacement factor d/a_{is} is calculated as a function of the ratio a_c/a_{is}. For the relationship shown in Figure 4.14, the range in estimated displacement factor is shown and it is assumed that there is a uniform probability distribution of displacement factors between the upper and lower bounds.

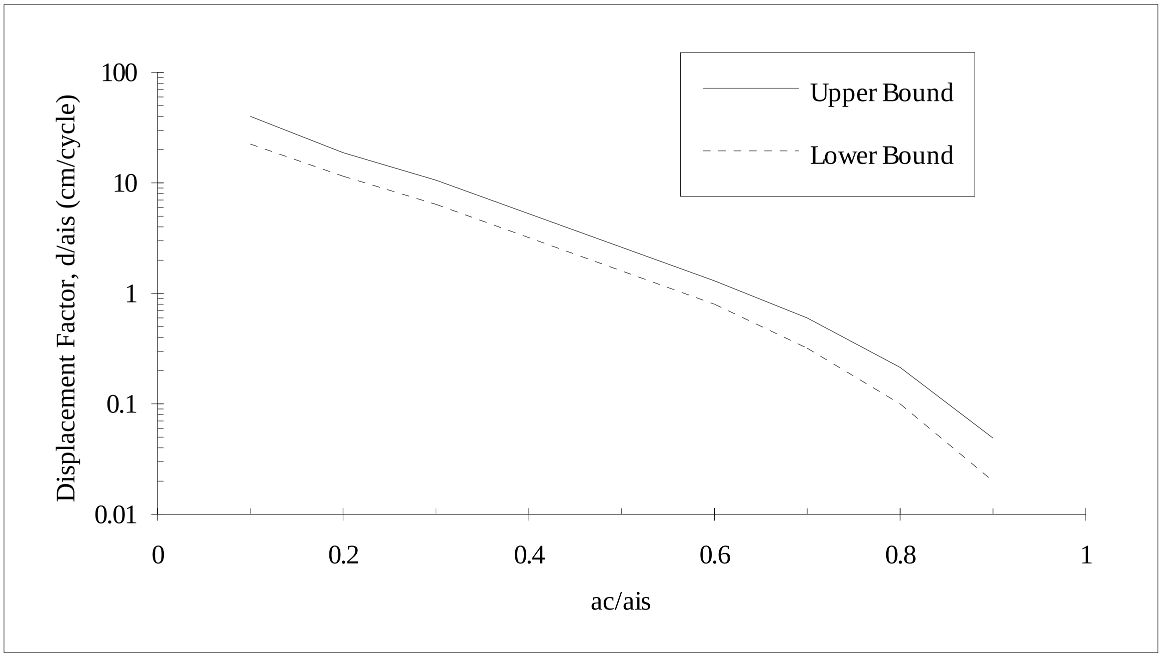


Figure 4.14 Relationship between Displacement Factor and Ratio of Critical Acceleration and Induced Acceleration.

4.2.2.3 Surface Fault Rupture

4.2.2.3.1 Permanent Ground Displacements

The correlation between surface fault displacement and earthquake moment magnitude (**M**) developed by Wells and Coppersmith (1994) is used. The maximum displacement is given by the relationship shown in Figure 4.16. It is assumed that the maximum displacement can potentially occur at any location along the fault, although at the ends of the fault, displacements must drop to zero. The relationship developed by Wells and Coppersmith based on their empirical data set for all types of faulting (strike slip, reverse and normal) is used. It is considered that this relationship provides reasonable estimates for any type of faulting for general loss estimation purposes. The uncertainty in the maximum displacement estimate is incorporated in the loss estimation analysis. The log of the standard deviation of estimate is equal to 0.35 which is equivalent to a factor of about 2 in the displacement estimate at the plus-or-minus one standard deviation level.

The median maximum displacement (MD) is given by the following relationship:

$$\log(\mathrm{MD}) = -5.26 + 0.79(\mathbf{M}) \tag{4-27}$$

where **M** is moment magnitude.

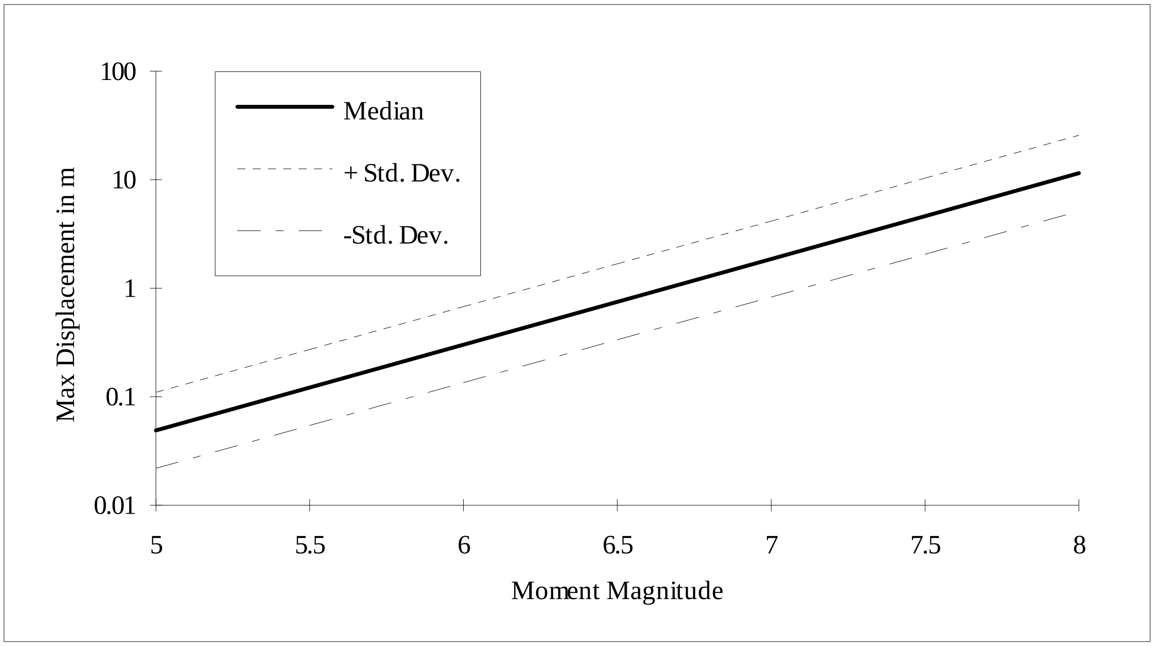


Figure 4.15 Relationship for Estimating Maximum Surface Fault Displacement.

It has been observed that displacements along a fault vary considerably in amplitude from zero to the maximum value. Wells and Coppersmith found that the average displacement along the fault rupture segment was approximately equal to one-half the maximum displacement. This is equivalent to a uniform probability distribution for values of displacement ranging from zero to the maximum displacement. As a conservative estimate, a uniform probability distribution from one-half of the maximum fault displacement to the maximum fault displacement is incorporated in the loss estimation methodology for any location along the fault rupture.

4.2.3 Guidance for Expert-Generated Ground Failure Estimation

This section provides guidance for users who wish to use more refined methods and data to prepare improved estimates of ground failure. It is assumed that such users would be geotechnical experts with sufficient expertise in ground failure prediction to develop site-specific estimates of PGD based on regional/local data.

4.2.3.1 Input Requirements and Output Information

4.2.3.1.1 Liquefaction

Input

- A map delineating areas of equal susceptibility (i.e., similar age, deposition, material properties, and ground water depth)
- Probability distribution of susceptibility variation within each area

- Relationships between liquefaction probability and ground acceleration for each susceptible area
- Maps delineating topographic conditions (i.e., slope gradients and/or free-face locations) and susceptible unit thicknesses
- Relationships between ground displacements (i.e., lateral spreading and settlement), and ground acceleration for each susceptible unit, including probability distribution for displacement; they may vary within a given susceptible unit depending on topographic and liquefied zone thickness conditions

Output

- Contour maps depicting liquefaction hazard and associated potential ground displacements

4.2.3.1.2 Landsliding

Input

- A map depicting areas of equal critical or yield acceleration a_c (i.e., the values of peak ground acceleration within the slide mass required to just initiate landsliding, that is, reduce the factor of safety to 1.0 at the instant of time a_c occurs)
- The probability distribution for a_c within each area
- The ratio between induced peak ground surface acceleration, a_i, and the peak ground acceleration within the slide mass a_{is} (note: could be a constant ratio or could vary for different areas). The value $a_{is}/a_i \leq 1$. The default ratio is 1.0
- Relationships between landslide displacement d induced acceleration a_{ic} and initial or yield acceleration a_c including the probability distribution for d. Different relationships can be specified for different areas. The default relationship between the displacement factor d/a_{is} and a_c/a_{is} is shown in Figure 4.14.

Output

- Contour maps depicting landsliding hazard and permanent ground displacements

4.2.3.1.3 Surface Fault Rupture

Input

- Predictive relationship for the maximum amount of fault displacement
- Specification of regions of the fault having lower maximum displacements
- Specifying other than the default relationship for the probability distribution between minimum and maximum amounts of fault rupture displacement

Output

- Amount of fault displacement at locations along the fault trace

4.2.3.2 Liquefaction

4.2.3.2.1 Background

The key for the user in defining analysis inputs is understanding the interrelationship among factors that significantly influence occurrence of liquefaction and associated ground displacement phenomena.

During earthquake ground shaking, induced cyclic shear creates a tendency in most soils to change volume by rearrangement of the soil-particle structure. In loose soils, this volume change tendency is to compact or densify the soil structure. For soils such as fine sands, silts and clays, permeability is sufficiently low such that undrained conditions prevail and no or insignificant volume change can occur during the ground shaking. To accommodate the volume decrease tendency, the soil responds by increases of pore-water pressure and corresponding decreases of intergranular effective stress. The relationship between volume change tendency and pore-water increase is described by Martin, et al. (1975). Egan and Sangrey (1978) discuss the relationship among compressibility characteristics, the potential amount of pore-water pressure generation and the subsequent loss of strength in various soil materials. In general, more compressible soils such as plastic silts or clays do not generate excess pore-water pressure as quickly or to as large an extent as less compressible soils such as sands. Therefore, silty and clayey soils tend to be less susceptible than sandy soils to liquefaction-type behaviors. Even within sandy soils, the presence of finer-grained materials affects susceptibility as is reflected in the correlations illustrated in Figure 4.16 prepared by Seed, et al. (1985) for use in simplified empirical procedures for evaluating liquefaction potential.

Excess pore-water pressure generation and strength loss potential are also highly dependent on the density of the soil, as may also be inferred from Figure 4.16. Density characteristics of soils in a deposit, notably sandy and silty soils, are reflected in penetration resistance measured, for example, during drilling and sampling an exploratory boring. Using penetration resistance data to help assess liquefaction hazard due to an earthquake is considered a reasonable engineering approach (Seed and Idriss, 1982; Seed, et. al., 1985; National Research Council, 1985), because many of the factors affecting penetration resistance affect the liquefaction resistance of sandy and silty soils in a similar way and because state-of-practice liquefaction evaluation procedures are based on actual performance of soil deposits during worldwide historical earthquakes (e.g., Figure 4.16).

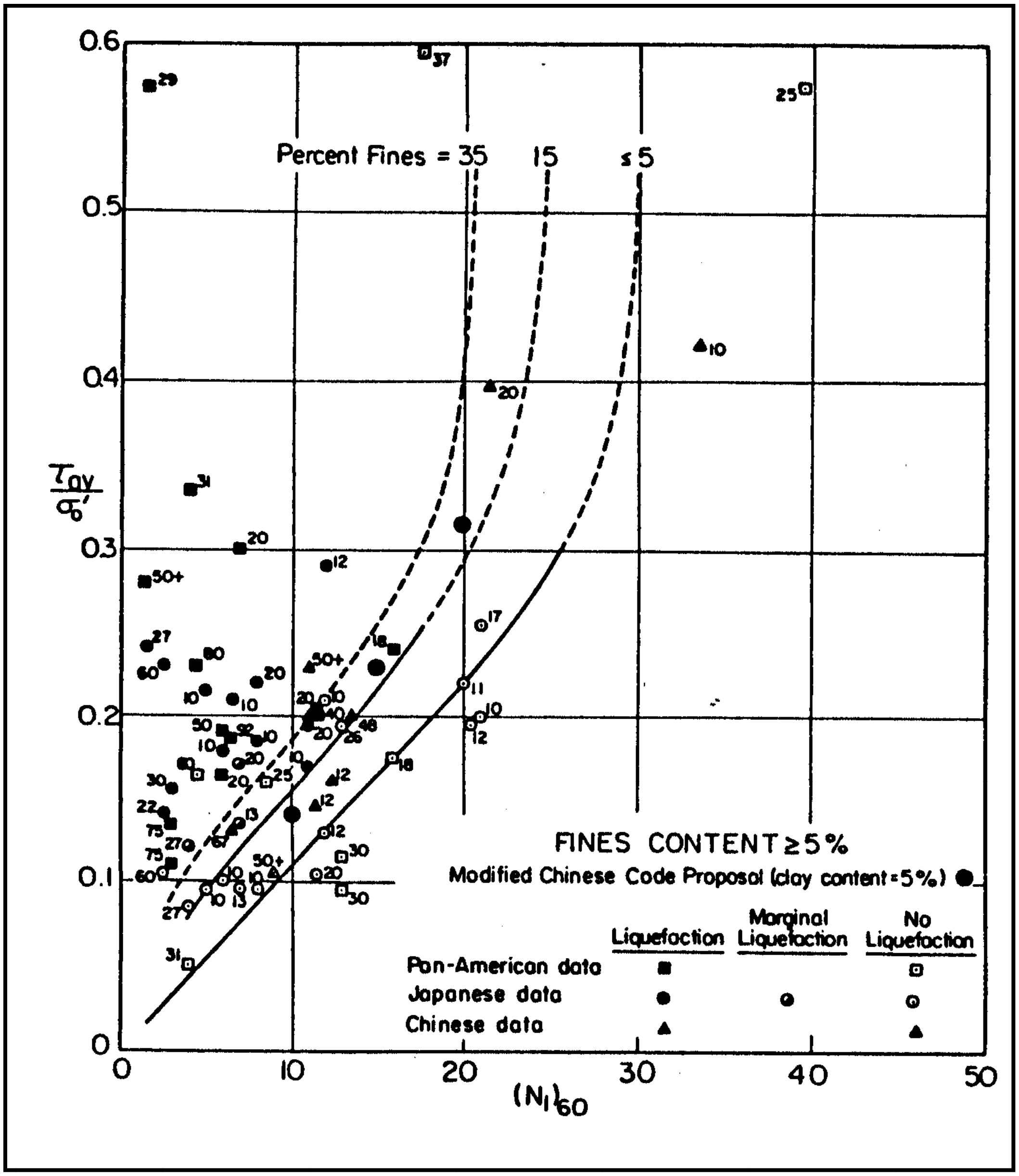


Figure 4.16 Relationship between Cyclic Stress Ratio causing Liquefaction and $(N_1)_{60}$ values (M=7.5) (Seed et al., 1985).

These displacement hazards are direct products of the soil behavior phenomena (i.e., high pore water pressure and significant strength reduction) produced by the liquefaction process. Lateral spreads are ground failure phenomena that occur near abrupt topographic features (i.e., free-faces) and on gently sloping ground underlain by liquefied soil. Earthquake ground-shaking affects the stability of sloping ground containing liquefiable materials by causing seismic inertia forces to be added to gravitational forces within the slope and by shaking-induced strength reductions in the liquefiable materials. Lateral spreading movements may be on the order of inches to several feet or more and are typically accompanied by surface fissures and slumping. Flow slides generally occur in liquefied materials found on steeper slopes and may involve ground movements of hundreds of feet. As a result, flowslides can be the most catastrophic of the liquefaction-related ground-failure phenomena. Fortunately, flow slides are much less common occurrences than lateral spreads.

Settlement is a result of the dissipation of excess pore pressure generated by the rearrangement of loosely compacted saturated soils into a denser configuration during shaking. Such dissipation will produce volume decreases (termed consolidation or compaction) within the soil that are manifested at the ground surface as settlement. Volume changes may occur in both liquefied and non-liquefied zones with significantly larger contributions to settlement expected to result from liquefied soil. Densification may also occur in loose unsaturated materials above the ground water table. Spatial variations in material characteristics may cause such settlements to occur differentially. Differential ground settlement may also occur near sand boil manifestations due to liquefied materials being removed from the depths of liquefaction and brought to the ground surface.

These factors have been discussed briefly in preceding sections and incorporated to the extent possible in characterizing relationships of Section 4.2.2.1. The challenge to the user is to translate regional/local data, experience and judgment into defining site-specific relationships. The following paragraphs offer additional comments regarding various aspects of that process.

4.2.3.2.2 Susceptibility

Fundamental soil characteristics and physical processes that affect liquefaction susceptibility have been identified through case histories and laboratory studies. Depositional environments of sediments and their geologic ages control these characteristics and processes, as discussed by Youd and Perkins (1978).

The depositional environments of sediments control grain size distribution and, in part, the relative density and structural arrangement of grains. Grain size characteristics of a soil influence its susceptibility to liquefaction. Fine sands tend to be more susceptible than silts and gravels. All cohesionless soils, however, may be considered potentially liquefiable as the influence of particle size distribution is not thoroughly understood. In general, cohesive soils that contain more than about 20 percent clay may be considered nonliquefiable (Seed and Idriss, 1982, present criteria for classifying a soil as nonliquefiable).

Relative density and structural arrangement of grains (soil structure) greatly influence liquefaction susceptibility of a cohesionless soil. Soils that have higher relative densities and more stable soil structure have a lower susceptibility to liquefaction. These factors may be related to both depositional environment and age. Sediments undisturbed after deposition (e.g., lagoon or bay deposits) tend to have lower densities and less stable structures than sediments subjected to wave or current action. With increasing age of a deposit, relative density may increase as particles gradually work closer together. The soil structure also may become more stable with age through slight particle reorientation or cementation. Also, the thickness of overburden sediments may increase with age, and the increased pressures associated with a thicker overburden will tend to increase the density of the soil deposit.

An increase in the ratio of effective lateral earth pressure to effective vertical or overburden earth pressure in a soil has been shown to reduce its liquefaction susceptibility. Such an increase will occur when overburden is removed by erosion.

In general, it is thought that the soil characteristics and processes that result in a lower liquefaction susceptibility also result in higher penetration resistance when a soil sampler is driven into a soil deposit. Therefore, blow count values, which measure penetration resistance of a soil sampler in a boring, are a useful indicator of liquefaction susceptibility. Similarly, the resistance from pushing a cone penetrometer into the soil is a useful indicator of liquefaction susceptibility. An understanding of the depositional environments and ages of soil units together with penetration resistance data enables assessment of liquefaction susceptibility.

Additional information helpful to enhancing/refining the susceptibility characterization is observation of liquefaction and related phenomena during historical earthquakes, as well as evidence of paleoliquefaction. Although such information does not exist for all locations and its absence does not preclude liquefaction susceptibility, it is available for numerous locations throughout the country; for example, in Northern California (Youd and Hoose, 1978; Tinsley, et. al., 1994). Incorporation of such historical information has been shown to significantly enhance liquefaction-related loss estimation.

4.2.3.2.3 Liquefaction Probability

As described previously, simplified procedures for evaluating liquefaction potential presented by Seed, et. al. (1985), as well as probabilistic approach presented by Liao, et al. (1988), are useful tools for helping to characterize the relationships among liquefaction probability, peak ground acceleration, duration of shaking (magnitude), and groundwater depth, etc. A parameter commonly utilized in these procedures is penetration resistance, which was previously discussed relative to susceptibility. Within a given geologic unit, experience indicates that subsurface investigations may obtain a certain scatter in penetration resistance without necessarily any observable trend for variation horizontally or vertically within that unit. In such cases, a single representative penetration resistance value is often selected for evaluating the liquefaction potential at the site. The representative value is very much site-specific and depends on the particular distribution of penetration resistance values measured. For example, if most of the values are very close to each other, with a few much higher or lower values, the representative value might be selected as the value that is close to the mean of the predominant population of values that are close to each other. On the other hand, if the penetration resistance values appear to be widely scattered over a fairly broad range of values, a value near the 33rd percentile might be more appropriate to select (H. B. Seed, personal communication, 1984). A typical distribution of penetration resistance (N_1) for a Holocene alluvial fan deposit (i.e., moderate susceptibility) is shown in Figure 4.17.

The user may elect to eliminate the probabilistic factor that quantifies the proportion of a geologic map unit deemed susceptible to liquefaction (i.e., the likelihood of susceptible conditions existing at any given location within the unit) if regional geotechnical data enables microzonation of susceptibility areas, or define this factor as a probabilistic distribution, or incorporate the susceptibility uncertainty in defining other liquefaction probability relationships.

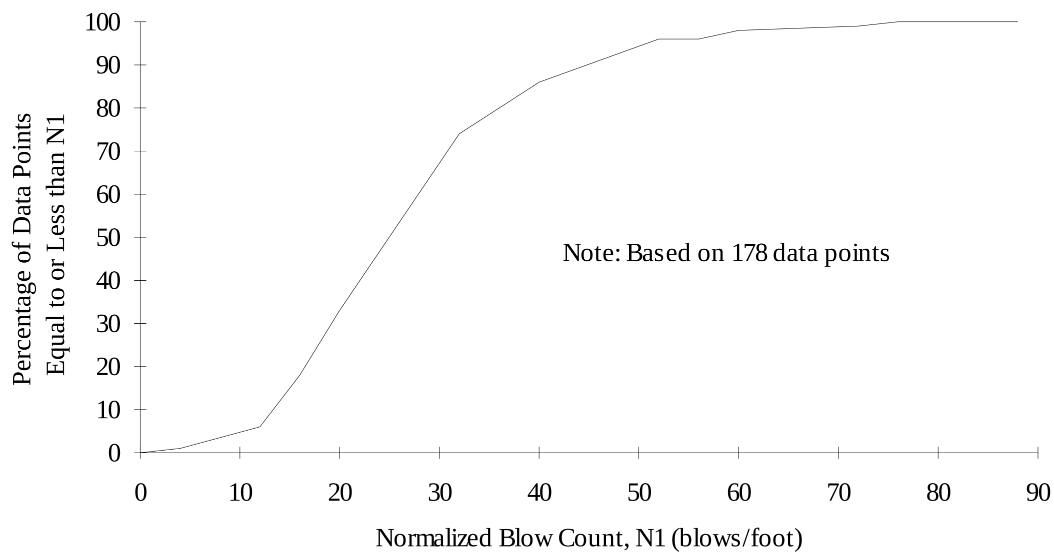


Figure 4.17 Typical Cumulative Distribution Curve of Penetration Resistance for Holocene Alluvial Fan Deposits (after Power, et. al., 1992).

4.2.3.2.4 Permanent Ground Displacement

<u>Lateral Spreading</u>

Various relationships for estimating lateral spreading displacement have been proposed, including the previously utilized Liquefaction Severity Index (LSI) by Youd and Perkins (1978), and a relationship by Bartlet and Youd (1992), in which they characterize displacement potential as a function of global earthquake and local site characteristics (e.g., slope, liquefaction thickness, and grain size distribution). Relationships that are more site-specific may be developed based on simple stability and deformation analysis for lateral spreading conditions using undrained residual strengths for liquefied sand (Seed and Harder, 1990) along with Newmark-type (1965) and Makdisi and Seed (1978) displacement approaches. To reasonably represent the lateral spreading hazard by either published relationships or area-specific analyses, generalized information regarding stratigraphic conditions (i.e., depth to and thickness of the liquefied zone) and topographic conditions (i.e., ground slope and free-face situations) are required.

<u>Ground Settlement</u>

Relationships for assessing ground settlement are available (e.g., Tokimatsu and Seed, 1978) and are suggested to the user for guidance. In addition, test results presented by Lee and Albaisa (1974) suggest that the magnitude of volumetric strain following liquefaction may be dependent on grain-size distribution. Area-specific information required for developing settlement relationships is similar to that for lateral spreading.

4.2.3.3 Landsliding

4.2.3.3.1 Background

The key assessment is the generation of a map denoting areas of equal landslide susceptibility and their corresponding values of critical acceleration. This should be accomplished considering the geographical distribution of facilities at risk in the region and the types of landsliding that could affect the facilities.

4.2.3.3.2 Landslide Susceptibility

Keefer (1984) and Wilson and Keefer (1985) have identified many different types of landsliding, ranging from rock falls to deep-seated coherent soil or rock slumps to soil lateral spreads and flows. For loss estimation purposes, the potential for lateral spreads and flows should be part of the liquefaction potential assessment rather than the landslide potential. The significance of other forms of downslope movement depends on the potential for such movements to damage facilities. The emphasis on characterizing landslide susceptibility should be on failure modes and locations that pose a significant risk to facilities. For example, if the potential for rock falls were high (because of steep terrain and weak rock) but could occur only in undeveloped areas, then it would not be important to characterize the critical acceleration for this mode of failure. As another example, in evaluating the probability of landsliding and the amount of displacements as part of a regional damage assessment for a utility district (Power et al., 1994), it was assessed that two types of landsliding posed the major risk to the facilities and piping: activation of existing deep-seated landslide deposits that had been mapped in hillside areas and that had the potential for disrupting areas in which water lines were located (landslides often covering many square blocks); and local slumping of roadway sidehill fills in which water lines were embedded.

Having identified the modes and geographic areas of potential landsliding of significance, critical acceleration can be evaluated for these modes and areas. It is not necessarily required to estimate a_c as a function of slope angle. In some cases, it may be satisfactory to estimate a_c and corresponding ranges of values for generalized types of landslides and subregions, for example, reactivation of existing landslides within a certain subregion or within the total region. However, it is usually necessary to distinguish between dry and wet conditions because a_c is usually strongly dependent on groundwater conditions.

In general, there are two approaches to estimating a_c: an empirical approach utilizing observations of landsliding in past earthquakes and corresponding records or estimates of ground acceleration; and an analytical approach, in which values of a_c are calculated by pseudo-static slope stability analysis methods. Often, both approaches may be utilized (Power, et. al., 1994). When using the analytical approach, the sensitivity of results to soil strength parameters must be recognized. In assessing strength parameter values and ranges, it is often useful to back-estimate values, which are operable during static conditions. Thus, for certain types of geology, slope angles, static performance observations during dry and wet seasons, and estimates of static factors of safety, it may be possible to infer reasonable ranges of strength parameters from static slope stability analyses. For earthquake loading conditions, an assessment should also be made as to whether the short-term dynamic, cyclic strength would differ from the static strength. If the soil or rock is not susceptible to strength degradation due to cyclic load applications or large deformations, then it may be appropriate to assign strength values higher than static values due to rate of loading effects. On the other hand, values even lower than static values may be appropriate if significant reduction in strength is expected (such as due to large-deformation-induced remolding of soil).

4.2.3.3.3 Probability of Landsliding

The probability of landsliding at any location is determined by comparing the induced peak ground acceleration (adjusted to the value of the peak acceleration in the landslide mass a_{is}) with the assessed distribution for critical acceleration a_c (Figure 4.19).

4.2.3.3.4 Permanent Ground Displacements

In assessing soil deformations using relationships such as shown in Figure 4.14, it should be kept in mind that the relationships are applicable to slope masses that exhibit essentially constant critical accelerations. For cases where significant reduction in strength may occur during the slope deformation process, these relationships may significantly underestimate deformations if the peak strength values are used. For example, deformations cannot be adequately estimated using these simplified correlations in cases of sudden, brittle failure, such as rock falls or soil or rock avalanches on steep slopes.

4.2.3.4 Surface Fault Rupture

4.2.3.4.1 Permanent Ground Displacements

Refinements or alternatives that an expert may wish to consider in assessing displacements associated with surface fault rupture include: a predictive relationship for maximum fault displacement different from the default relationship (Figure 4.15), specification of regions of the fault rupture (near the ends) where the maximum fault displacement is constrained to lower values, and specification of other than the default relationship for the probability distribution of fault rupture between minimum and maximum values.

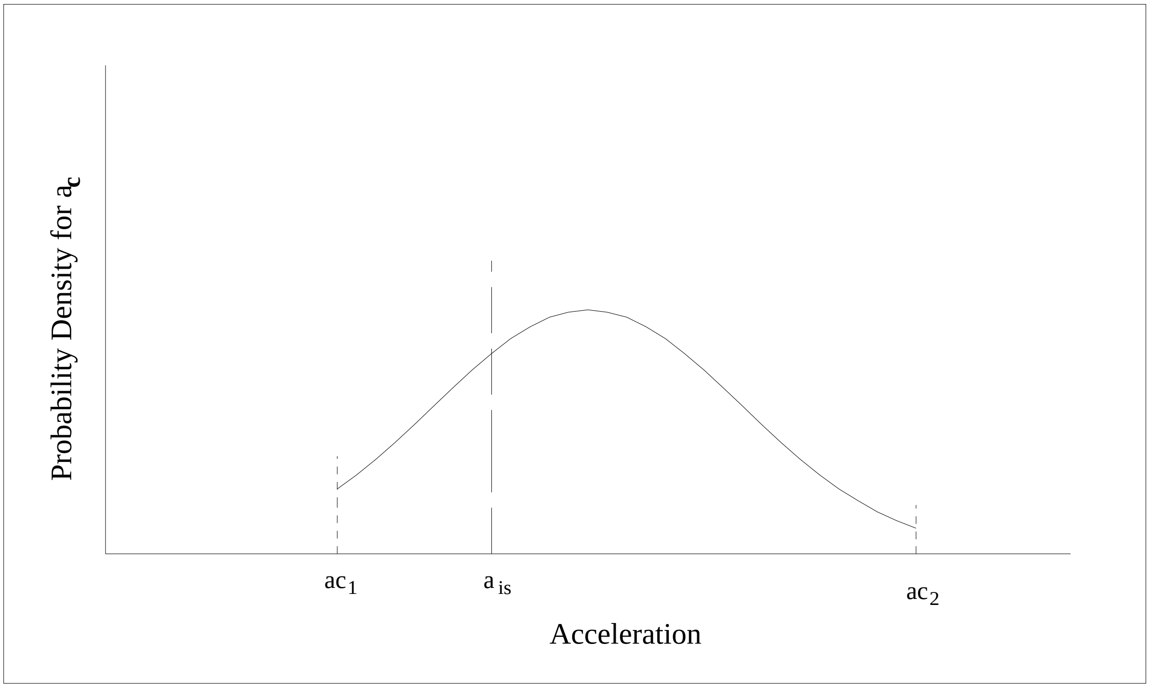


Figure 4.18 Evaluation of Probability of Landsliding.

4.3 References

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Chapter 5
Direct Physical Damage - General Building Stock

5.1 Introduction

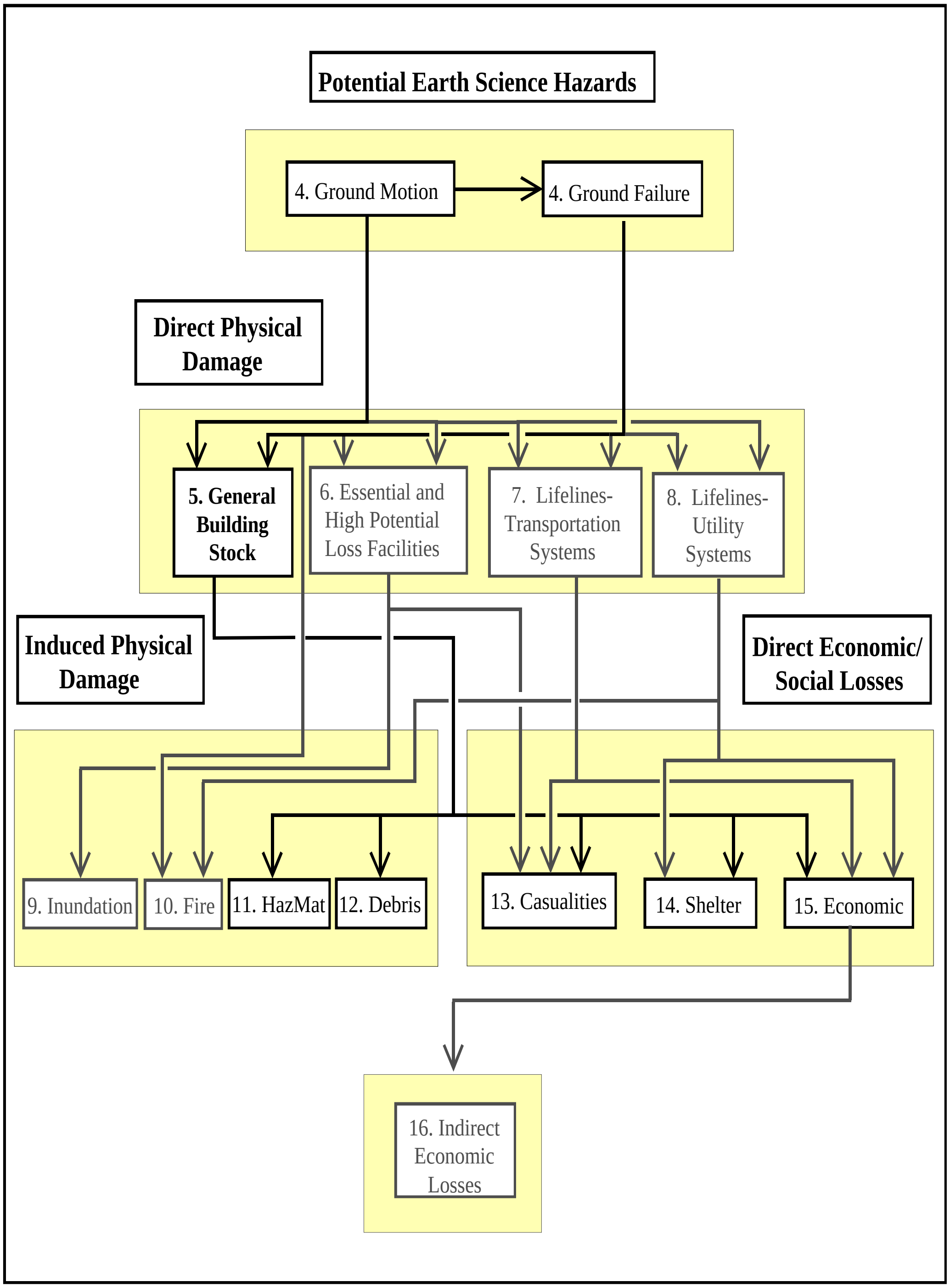
This chapter describes methods for determining the probability of Slight, Moderate, Extensive and Complete damage to general building stock. General building stock represents typical buildings of a given model building type designed to either High-Code, Moderate-Code, or Low-Code seismic standards, or not seismically designed (referred to as Pre-Code buildings). Chapter 6 describes methods for estimating earthquake damage to essential facilities that include Special buildings designed and constructed to standards above normal Code provisions. The flowchart of the overall methodology, highlighting the building damage component and showing its relationship to other components, is shown in Flowchart 5-1.

5.1.1 Scope

The scope of this chapter includes development of methods for estimation of earthquake damage to buildings given knowledge of the model building type and an estimate of the level of ground shaking (or degree of ground failure). Model building types are defined in Section 5.2. The extent and severity of damage to structural and nonstructural components of a building is described by one of five damage states**:** None, Slight, Moderate, Extensive, and Complete. Damage states are defined in Section 5.3 for each model building type by physical descriptions of damage to building elements.

This chapter focuses on the development of functions for estimating building damage due to ground shaking. These building damage functions include: (1) fragility curves that describe the probability of reaching or exceeding different states of damage given peak building response, and (2) building capacity (push-over) curves that are used (with damping-modified demand spectra) to determine peak building response. For use in lifeline damage evaluation, a separate set of building fragility curves expresses the probability of structural damage in terms of peak ground acceleration (PGA). Building damage functions for ground shaking are described in Section 5.4 for each model building type.

While ground shaking typically dominates damage to buildings, ground failure can also be a significant contributor to building damage. Ground failure is characterized by permanent ground deformation (PGD) and fragility curves are used to describe the probability of reaching different states of damage given PGD. These fragility curves are similar to, but less detailed than, those used to estimate damage due to ground shaking. Building damage functions for ground failure are described in Section 5.5.



Flowchart 5.1 Building Damage Relationship to Other Components of the Methodology

Section 5.6 describes implementation of ground shaking damage functions (including development of damping-modified demand spectra) and the calculation of the probability of combined ground shaking and ground failure damage.

The methods described in this chapter may also be used by seismic/structural engineering experts to modify default damage functions (based on improved knowledge of building types, their structural properties and design vintage). Guidance for expert users is provided in Section 5.7

5.1.2 Input Requirements and Output Information

Input required to estimate building damage using fragility and capacity curves includes the following two items:

- model building type (including height) and seismic design level that represents the building (or group of buildings) of interest, and

- response spectrum (or PGA, for lifeline buildings, and PGD for ground failure evaluation) at the building's site or at the centroid of the census tract area where the building (or group of buildings) is located.

Typically, the model building type is not known for each building and must be determined from the inventory of facilities using the relationship of building type and occupancy, described in Chapter 3. The response spectrum, PGA and PGD at the building site (or census tract centroid) are PESH outputs, described in Chapter 4.

The "output" of fragility curves is an estimate of the cumulative probability of being in, or exceeding, each damage state for the given level of ground shaking (or ground failure). Discrete damage state probabilities are created using cumulative damage probabilities, as described in Section 5.6. Discrete damage state probabilities for model building types and occupancy classes are the outputs of the building damage module. These outputs are used directly as inputs to induced physical damage and direct economic and social loss modules, as shown in Flowchart 5.1. While the fragility and capacity curves are applicable, in theory, to a single building as well as to all buildings of given type, they are more reliable as predictors of damage for large, rather than small, population groups. They should not be considered reliable for prediction of damage to a specific facility without confirmation by a seismic/structural engineering expert.

5.1.3 Form of Damage Functions

Building damage functions are in the form of lognormal fragility curves that relate the probability of being in, or exceeding, a building damage state to for a given PESH demand parameter (e.g., response spectrum displacement). Figure 5.1 provides an example of fragility curves for the four damage states used in this methodology.

Each fragility curve is defined by a median value of the PESH demand parameter (i.e., either spectral displacement, spectral acceleration, PGA or PGD) that corresponds to the threshold of the damage state and by the variability associated with that damage state. For example, the spectral displacement, S_d, that defines the threshold of a particular damage state (ds) is assumed to be distributed by:

$$S_d = \overline{S}_{d,ds} \bullet \varepsilon_{ds} \tag{5-1}$$

where: $\overline{S}_{d,ds}$ is the median value of spectral displacement of damage state, ds, and

ε_{ds} is a lognormal random variable with unit median value and logarithmic standard deviation, β_{ds}.

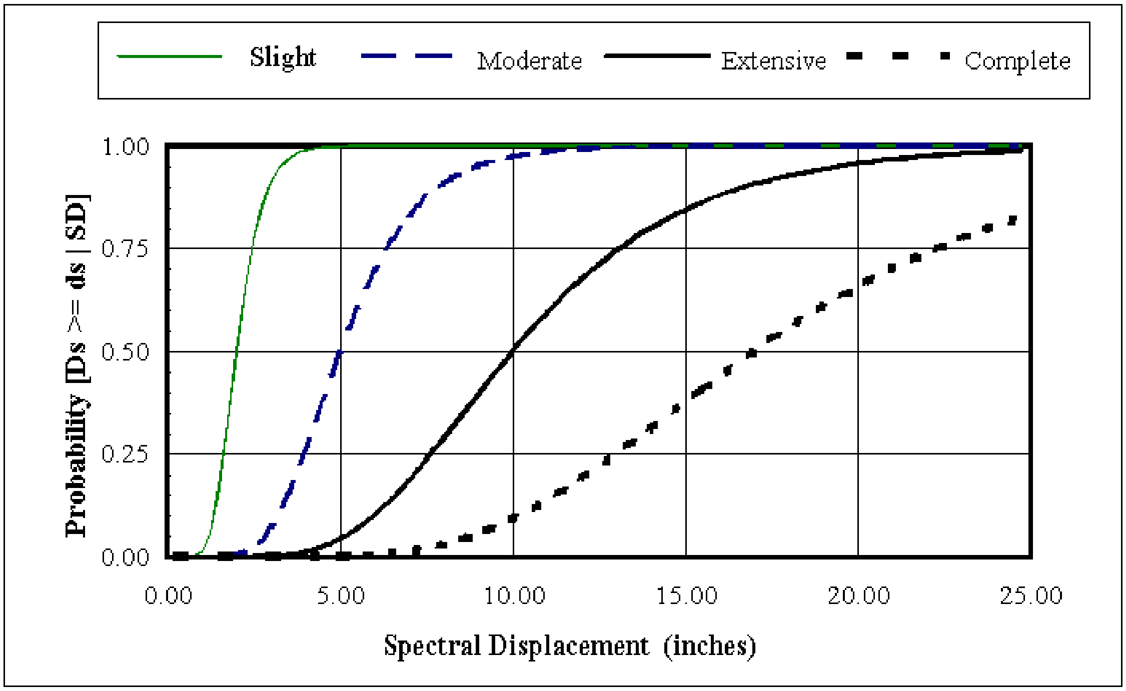


Figure 5.1 Example Fragility Curves for Slight, Moderate, Extensive and Complete Damage.

In a more general formulation of fragility curves, the lognormal standard deviation, β, has been expressed in terms of the randomness and uncertainty components of variability, β_R and β_U, [Kennedy, et. al., 1980]. Since it is not considered practical to separate uncertainty from randomness, the combined random variable term, β, is used to develop a composite "best-estimate" fragility curve. This approach is similar to that used to develop fragility curves for the FEMA-sponsored study of consequences of large earthquakes on six cities of the Mississippi Valley region [Allen & Hoshall, et al., 1985].

The conditional probability of being in, or exceeding, a particular damage state, ds, given the spectral displacement, S_d, (or other PESH parameter) is defined by the function:

$$P\left[ds \middle| S_d\right] = \Phi\left[\frac{1}{\beta_{ds}} \ln\left(\frac{S_d}{\overline{S}_{d,ds}}\right)\right] \quad (5\text{-}2)$$

where: $\overline{S}_{d,ds}$ is the median value of spectral displacement at which the building reaches the threshold of damage state, ds,

βds is the standard deviation of the natural logarithm of spectral displacement for damage state, ds, and

Φ is the standard normal cumulative distribution function.

Median spectral displacement (or acceleration) values and the total variability are developed for each of the model building types and damage states of interest by the combination of performance data (from tests of building elements), earthquake experience data, expert opinion and judgment.

In general, the total variability of each damage state, β_{ds}, is modeled by the combination of following three contributors to damage variability:

- uncertainty in the damage state threshold,
- variability in the capacity (response) properties of the model building type of interest, and

- uncertainty in response due to the spatial variability of ground motion demand.

Each of these three contributors to damage state variability is assumed to be lognormally distributed random variables.

The fragility curves are driven by a PESH parameter. For ground failure, the PESH parameter used to drive fragility curves is permanent ground displacement (PGD). For ground shaking, the PESH parameter used to drive building fragility curves is peak spectral response (either displacement or acceleration). Peak ground acceleration (PGA), rather than peak spectral displacement, is used to evaluate ground shaking-induced structural damage to buildings that are components of lifelines (see Section 5.4.4). Peak spectral response varies significantly for buildings that have different response properties (e.g., tall, flexible buildings will displace more than short, stiff buildings). Therefore, determination of peak spectral displacement requires knowledge of the building's response properties.

Building response is characterized by building capacity curves. These curves describe the push-over displacement of each building type and seismic design level as a function of laterally-applied earthquake load. The Methodology uses a technique, similar to the capacity spectrum method [Mahaney, et. al., 1993], to estimate peak building response as the intersection of the building capacity curve and the response spectrum of PESH shaking demand at the building's location (demand spectrum). The capacity spectrum method is one of the two nonlinear static analysis methods described in the *NEHRP Guidelines for the Seismic Rehabilitation of Buildings* [FEMA, 1996a] and developed more extensively in *Seismic Evaluation and Retrofit of Concrete Buildings* [SSC, 1996].

The demand spectrum is the 5%-damped PESH input spectrum reduced for higher levels of effective damping (e.g., effective damping includes both elastic damping and hysteretic damping associated with post-yield cyclic response of the building). Figure 5.2 illustrates the intersection of a typical building capacity curve and a typical demand spectrum (reduced for effective damping greater than 5% of critical). Design-, yield- and ultimate-capacity points define the shape of building capacity curves. Peak building response (either spectral displacement or spectral acceleration) at the point of intersection of the capacity curve and demand spectrum is the parameter used with fragility curves to estimate damage state probabilities (see also Section 5.6.2.2).

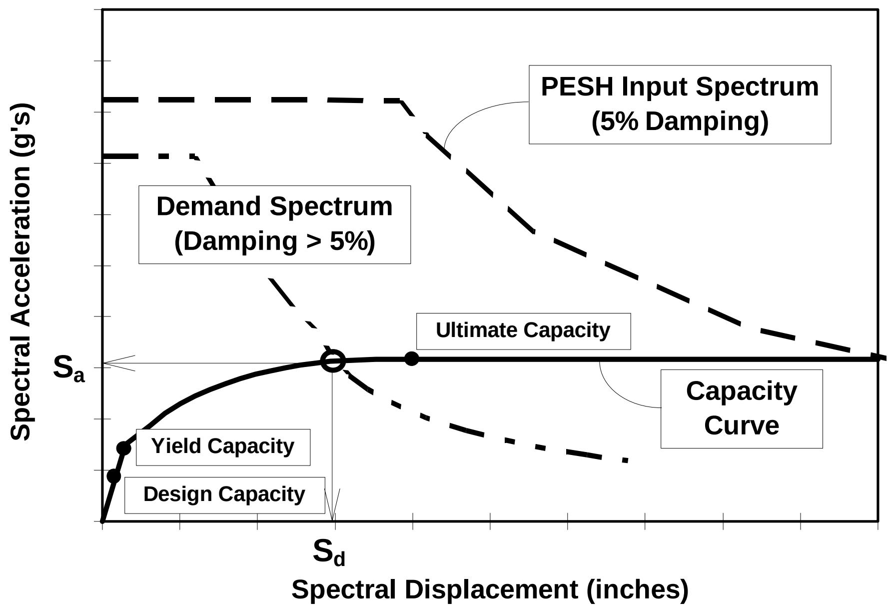


Figure 5.2 Example Building Capacity Curve and Demand Spectrum.

5.2 Description of Model Building Types

Table 5.1 lists the 36 model building types that are used by the Methodology. These model building types are based on the classification system of FEMA 178, *NEHRP Handbook for the Seismic Evaluation of Existing Buildings* [FEMA, 1992]. In addition, the methodology breaks down FEMA 178 classes into height ranges, and also includes mobile homes.

Table 5.1 Model Building Types

No.	Label	Description	Height			
			Range		Typical	
			Name	Stories	Stories	Feet
1 2	W1 W2	**Wood, Light Frame (≤ 5,000 sq. ft.)** **Wood, Commercial and Industrial (> 5,000 sq. ft.)**		1 - 2 All	1 2	14 24
3 4	S1L S1M	**Steel Moment Frame**	Low-Rise Mid-Rise	1 - 3 4 - 7	2 5	24 60

5	S1H		High-Rise	8+	13	156
6	S2L	**Steel Braced Frame**	Low-Rise	1 - 3	2	24
7	S2M		Mid-Rise	4 - 7	5	60
8	S2H		High-Rise	8+	13	156
9	S3	**Steel Light Frame**		All	1	15
10	S4L	**Steel Frame with Cast-in-Place Concrete Shear Walls**	Low-Rise	1 - 3	2	24
11	S4M		Mid-Rise	4 - 7	5	60
12	S4H		High-Rise	8+	13	156
13	S5L	**Steel Frame with Unreinforced Masonry Infill Walls**	Low-Rise	1 - 3	2	24
14	S5M		Mid-Rise	4 - 7	5	60
15	S5H		High-Rise	8+	13	156
16	C1L	**Concrete Moment Frame**	Low-Rise	1 – 3	2	20
17	C1M		Mid-Rise	4 - 7	5	50
18	C1H		High-Rise	8+	12	120
19	C2L	**Concrete Shear Walls**	Low-Rise	1 - 3	2	20
20	C2M		Mid-Rise	4 - 7	5	50
21	C2H		High-Rise	8+	12	120
22	C3L	**Concrete Frame with Unreinforced Masonry Infill Walls**	Low-Rise	1 - 3	2	20
23	C3M		Mid-Rise	4 - 7	5	50
24	C3H		High-Rise	8+	12	120
25	PC1	**Precast Concrete Tilt-Up Walls**		All	1	15
26	PC2L	**Precast Concrete Frames with Concrete Shear Walls**	Low-Rise	1 - 3	2	20
27	PC2M		Mid-Rise	4 - 7	5	50
28	PC2H		High-Rise	8+	12	120
29	RM1L	**Reinforced Masonry Bearing Walls with Wood or Metal Deck Diaphragms**	Low-Rise	1-3	2	20
30	RM1M		Mid-Rise	4+	5	50

31	RM2L	**Reinforced Masonry Bearing Walls with Precast Concrete Diaphragms**	Low-Rise	1 - 3	2	20
32	RM2M		Mid-Rise	4 - 7	5	50
33	RM2H		High-Rise	8+	12	120
34	URML	**Unreinforced Masonry Bearing Walls**	Low-Rise	1 - 2	1	15
35	URMM		Mid-Rise	3+	3	35
36	MH	**Mobile Homes**		All	1	10

5.2.1 Structural Systems

A general description of each of the 16 structural systems of model building types is given in the following sections.

Wood, Light Frame (W1):

These are typically single-family or small, multiple-family dwellings of not more than 5,000 square feet of floor area. The essential structural feature of these buildings is repetitive framing by wood rafters or joists on wood stud walls. Loads are light and spans are small. These buildings may have relatively heavy masonry chimneys and may be partially or fully covered with masonry veneer. Most of these buildings, especially the single-family residences, are not engineered but constructed in accordance with "conventional construction" provisions of building codes. Hence, they usually have the components of a lateral-force-resisting system even though it may be incomplete. Lateral loads are transferred by diaphragms to shear walls. The diaphragms are roof panels and floors that may be sheathed with sawn lumber, plywood or fiberboard sheathing. Shear walls are sheathed with boards, stucco, plaster, plywood, gypsum board, particle board, or fiberboard, or interior partition walls sheathed with plaster or gypsum board.

Wood, Greater than 5,000 Sq. Ft. (W2):

These buildings are typically commercial or industrial buildings, or multi-family residential buildings with a floor area greater than 5,000 square feet. These buildings include structural systems framed by beams or major horizontally spanning members over columns. These horizontal members may be glue-laminated (glu-lam) wood, solid-sawn wood beams, or wood trusses, or steel beams or trusses. Lateral loads usually are resisted by wood diaphragms and exterior walls sheathed with plywood, stucco, plaster, or other paneling. The walls may have diagonal rod bracing. Large openings for stores and garages often require post-and-beam framing. Lateral load resistance on those lines may be achieved with steel rigid frames (moment frames) or diagonal bracing.

Steel Moment Frame (S1):

These buildings have a frame of steel columns and beams. In some cases, the beam-column connections have very small moment resisting capacity but, in other cases, some of the beams and columns are fully developed as moment frames to resist lateral forces. Usually the structure is concealed on the outside by exterior nonstructural walls, which can be of almost any material (curtain walls, brick masonry, or precast concrete panels), and on the inside by ceilings and column furring. Diaphragms transfer lateral loads to moment-resisting frames. The diaphragms can be almost any material. The frames develop their stiffness by full or partial moment connections. The frames can be located almost anywhere in the building. Usually the columns have their strong directions oriented so that some columns act primarily in one direction while the others act in the other direction. Steel moment frame buildings are typically more flexible than shear wall buildings. This low stiffness can result in large interstory drifts that may lead to relatively greater nonstructural damage.

Steel Braced Frame (S2):

These buildings are similar to steel moment frame buildings except that the vertical components of the lateral-force-resisting system are braced frames rather than moment frames.

Steel Light Frame (S3):

These buildings are pre-engineered and prefabricated with transverse rigid frames. The roof and walls consist of lightweight panels, usually corrugated metal. The frames are designed for maximum efficiency, often with tapered beam and column sections built up of light steel plates. The frames are built in segments and assembled in the field with bolted joints. Lateral loads in the transverse direction are resisted by the rigid frames with loads distributed to them by diaphragm elements, typically rod-braced steel roof framing bays. Tension rod bracing typically resists loads in the longitudinal direction.

Steel Frame with Cast-In-Place Concrete Shear Walls (S4):

The shear walls in these buildings are cast-in-place concrete and may be bearing walls. The steel frame is designed for vertical loads only. Diaphragms of almost any material transfer lateral loads to the shear walls. The steel frame may provide a secondary lateral-force-resisting system depending on the stiffness of the frame and the moment capacity of the beam-column connections. In modern "dual" systems, the steel moment frames are designed to work together with the concrete shear walls.

Steel Frame with Unreinforced Masonry Infill Walls (S5):

This is one of the older types of buildings. The infill walls usually are offset from the exterior frame members, wrap around them, and present a smooth masonry exterior with no indication of the frame. Solidly infilled masonry panels, when they fully engage the surrounding frame members (i.e. lie in the same plane), may provide stiffness and lateral load resistance to the structure.

Reinforced Concrete Moment Resisting Frames (C1):

These buildings are similar to steel moment frame buildings except that the frames are reinforced concrete. There are a large variety of frame systems. Some older concrete frames may be proportioned and detailed such that brittle failure of the frame members can occur in earthquakes leading to partial or full collapse of the buildings. Modern frames in zones of high seismicity are proportioned and detailed for ductile behavior and are likely to undergo large deformations during an earthquake without brittle failure of frame members and collapse.

Concrete Shear Walls (C2):

The vertical components of the lateral-force-resisting system in these buildings are concrete shear walls that are usually bearing walls. In older buildings, the walls often are quite extensive and the wall stresses are low but reinforcing is light. In newer buildings, the shear walls often are limited in extent, generating concerns about boundary members and overturning forces.

Concrete Frame Buildings with Unreinforced Masonry Infill Walls (C3):

These buildings are similar to steel frame buildings with unreinforced masonry infill walls except that the frame is of reinforced concrete. In these buildings, the shear strength of the columns, after cracking of the infill, may limit the semi-ductile behavior of the system.

Precast Concrete Tilt-Up Walls (PC1):

These buildings have a wood or metal deck roof diaphragm, which often is very large, that distributes lateral forces to precast concrete shear walls. The walls are thin but relatively heavy while the roofs are relatively light. Older or non-seismic-code buildings often have inadequate connections for anchorage of the walls to the roof for out-of-plane forces, and the panel connections often are brittle. Tilt-up buildings usually are one or two stories in height. Walls can have numerous openings for doors and windows of such size that the wall looks more like a frame than a shear wall.

Precast Concrete Frames with Concrete Shear Walls (PC2):

These buildings contain floor and roof diaphragms typically composed of precast concrete elements with or without cast-in-place concrete topping slabs. Precast concrete girders and columns support the diaphragms. The girders often bear on column corbels. Closure strips between precast floor elements and beam-column joints usually are cast-in-place concrete. Welded steel inserts often are used to interconnect precast elements. Precast or cast-in-place concrete shear walls resist lateral loads. For buildings with precast frames and concrete shear walls to perform well, the details used to connect the structural elements must have sufficient strength and displacement capacity; however, in some cases, the connection details between the precast elements have negligible ductility.

Reinforced Masonry Bearing Walls with Wood or Metal Deck Diaphragms (RM1):

These buildings have perimeter bearing walls of reinforced brick or concrete-block masonry. These walls are the vertical elements in the lateral-force-resisting system. The floors and roofs are framed with wood joists and beams either with plywood or braced sheathing, the latter either straight or diagonally sheathed, or with steel beams with metal deck with or without concrete fill. Interior wood posts or steel columns support wood floor framing; steel columns support steel beams.

Reinforced Masonry Bearing Walls with Precast Concrete Diaphragms (RM2):

These buildings have bearing walls similar to those of reinforced masonry bearing wall structures with wood or metal deck diaphragms, but the roof and floors are composed of precast concrete elements such as planks or tee-beams and the precast roof and floor elements are supported on interior beams and columns of steel or concrete (cast-in-place or precast). The precast horizontal elements often have a cast-in-place topping.

Unreinforced Masonry Bearing Walls (URM):

These buildings include structural elements that vary depending on the building's age and, to a lesser extent, its geographic location. In buildings built before 1900, the majority of floor and roof construction consists of wood sheathing supported by wood framing. In large multistory buildings, the floors are cast-in-place concrete supported by the unreinforced masonry walls and/or steel or concrete interior framing. In unreinforced masonry constructed after 1950 (outside California) wood floors usually have plywood rather than board sheathing. In regions of lower seismicity, buildings of this type constructed more recently can include floor and roof framing that consists of metal deck and concrete fill supported by steel framing elements. The perimeter walls, and possibly some interior walls, are unreinforced masonry. The walls may or may not be anchored to the diaphragms. Ties between the walls and diaphragms are more common for the bearing walls than for walls that are parallel to the floor framing. Roof ties usually are less common and more erratically spaced than those at the floor levels. Interior partitions that interconnect the floors and roof can reduce diaphragm displacements.

Mobile Homes (MH):

These are prefabricated housing units that are trucked to the site and then placed on isolated piers, jack stands, or masonry block foundations (usually without any positive anchorage). Floors and roofs of mobile homes usually are constructed with plywood and outside surfaces are covered with sheet metal.

5.2.2 Nonstructural Components

Nonstructural components include a large variety of different architectural, mechanical and electrical components (e.g., components listed in the NEHRP seismic design provisions for new buildings [FEMA, 1997a]). Contents of the buildings are treated as a separate category. Nonstructural components are grouped as either "drift-sensitive" or "acceleration-sensitive" components, in order to assess their damage due to an earthquake. Damage to drift-sensitive nonstructural components is primarily a function of interstory drift; damage to acceleration-sensitive nonstructural components and building contents is primarily a function of floor acceleration. Table 5.2 lists typical nonstructural components and building contents, and identifies each item as drift-sensitive or acceleration sensitive.

Anchorage/bracing of nonstructural components improves earthquake performance of most components although routine or typical anchorage/bracing provides only limited damage protection. It is assumed that typical nonstructural components and building contents have limited anchorage/bracing. Exceptions, such as special anchorage/bracing requirements for nonstructural components and contents of hospitals are addressed in Chapter 6. Nonstructural damage evaluation is dependent upon the response and performance of structural components, as well as being influenced by characteristics of nonstructural components themselves. Nonstructural damage simplifying assumptions are outlined in the following sections.

Table 5.2 List of Typical Nonstructural Components and Contents of Buildings

Type	**Item**	Drift-Sensitive*	Acceleration-Sensitive*
Architectural	Nonbearing Walls/Partitions	•	○
	Cantilever Elements and Parapets		•
	Exterior Wall Panels	•	○
	Veneer and Finishes	•	○
	Penthouses	•	
	Racks and Cabinets		•
	Access Floors		•
	Appendages and Ornaments		•
Mechanical and Electrical	General Mechanical (boilers, etc.)		•
	Manufacturing and Process Machinery		•
	Piping Systems	○	•
	Storage Tanks and Spheres		•
	HVAC Systems (chillers, ductwork, etc.)	○	•
	Elevators	○	•
	Trussed Towers		•
	General Electrical (switchgear, ducts, etc.)	○	•
	Lighting Fixtures		•
Contents	File Cabinets, Bookcases, etc.		•
	Office Equipment and Furnishings		•
	Computer/Communication Equipment		•
	Nonpermanent Manufacturing Equipment		•
	Manufacturing/Storage Inventory		•
	Art and other Valuable Objects		•

* Solid dots indicate primary cause of damage, open dots indicate secondary cause of damage

5.3 Description of Building Damage States

The results of damage estimation methods described in this chapter (i.e., damage predictions for model building types for a given level of ground shaking) are used in other modules of the methodology to estimate: (1) casualties due to structural damage, including fatalities, (2) monetary losses due to building damage (i.e. cost of repairing or replacing damaged buildings and their contents); (3) monetary losses resulting from building damage and closure (e.g., losses due to business interruption); (4) social impacts (e.g., loss of shelter); and, (5) other economic and social impacts.

The building damage predictions may also be used to study expected damage patterns in a given region for different scenario earthquakes (e.g., to identify the most vulnerable building types, or the areas expected to have the most damaged buildings).

In order to meet the needs of such broad purposes, damage predictions must allow the user to glean the nature and extent of the physical damage to a building type from the damage prediction output so that life-safety, societal functional and monetary losses which result from the damage can be estimated. Building damage can best be described in terms of its components (beams, columns, walls, ceilings, piping, HVAC equipment, etc.). For example, such component damage descriptions as “shear walls are cracked”, “ceiling tiles fell”, “diagonal bracing buckled”, “wall panels fell out”, etc. used together with such terms as “some” and “most” would be sufficient to describe the nature and extent of overall building damage.

Damage to nonstructural components of buildings (i.e., architectural components, such as partition walls and ceilings, and building mechanical/electrical systems) primarily affects monetary and societal functional losses and generates numerous casualties of mostly light-to-moderate severity. Damage to structural components (i.e., the gravity and lateral-load-resisting systems) of buildings, Hazard mitigation measures are different for these two categories of building components as well. Hence, it is desirable to separately estimate structural and nonstructural damage.

Building damage varies from “none” to “complete” as a continuous function of building deformations (building response). Wall cracks may vary from invisible or “hairline cracks” to cracks of several inches wide. Generalized “ranges” of damage are used by the Methodology to describe structural and nonstructural damage, since it is not practical to describe building damage as a continuous function.

The Methodology predicts a structural and nonstructural damage state in terms of one of four ranges of damage or “damage states”: Slight, Moderate, Extensive, and Complete. For example, the Slight damage state extends from the threshold of Slight damage up to the threshold of Moderate damage. General descriptions of these damage states are provided for all model building types with reference to observable damage incurred by structural (Section 5.3.1) and nonstructural building components (Section 5.3.2). Damage predictions resulting from this physical damage estimation method are then expressed in terms of the probability of a building being in any of these four damage states.

5.3.1 Structural Damage

Descriptions for Slight, Moderate, Extensive, and Complete structural damage states for the 16 basic model building types are provided below. For estimating casualties, the descriptions of Complete damage include the fraction of the total floor area of each model building type that is likely to collapse. Collapse fractions are based on judgment and limited earthquake data considering the material and construction of different model building types.

It is noted that in some cases the structural damage is not directly observable because the structural elements are inaccessible or not visible due to architectural finishes or fireproofing. Hence, these structural damage states are described, when necessary, with reference to certain effects on nonstructural elements that may be indicative of the structural damage state of concern. Small cracks are assumed, throughout this section, to be visible cracks with a maximum width of less than 1/8”. Cracks wider than 1/8” are referred to as “large” cracks.

Wood, Light Frame (W1):

Slight Structural Damage: Small plaster or gypsum-board cracks at corners of door and window openings and wall-ceiling intersections; small cracks in masonry chimneys and masonry veneer.

Moderate Structural Damage: Large plaster or gypsum-board cracks at corners of door and window openings; small diagonal cracks across shear wall panels exhibited by small cracks in stucco and gypsum wall panels; large cracks in brick chimneys; toppling of tall masonry chimneys.

Extensive Structural Damage: Large diagonal cracks across shear wall panels or large cracks at plywood joints; permanent lateral movement of floors and roof; toppling of most brick chimneys; cracks in foundations; splitting of wood sill plates and/or slippage of structure over foundations; partial collapse of “room-over-garage” or other “soft-story” configurations; small foundations cracks.

Complete Structural Damage: Structure may have large permanent lateral displacement, may collapse, or be in imminent danger of collapse due to cripple wall failure or the failure of the lateral load resisting system; some structures may slip and fall off the foundations; large foundation cracks. Approximately 3% of the total area of W1 buildings with Complete damage is expected to be collapsed.

Wood, Commercial and Industrial (W2):

Slight Structural Damage: Small cracks at corners of door and window openings and wall-ceiling intersections; small cracks on stucco and plaster walls. Some slippage may be observed at bolted connections.

Moderate Structural Damage: Larger cracks at corners of door and window openings; small diagonal cracks across shear wall panels exhibited by cracks in stucco and gypsum wall panels; minor slack (less than 1/8" extension) in diagonal rod bracing requiring re-tightening; minor lateral set at store fronts and other large openings; small cracks or wood splitting may be observed at bolted connections.

Extensive Structural Damage: Large diagonal cracks across shear wall panels; large slack in diagonal rod braces and/or broken braces; permanent lateral movement of floors and roof; cracks in foundations; splitting of wood sill plates and/or slippage of structure over foundations; partial collapse of "soft-story" configurations; bolt slippage and wood splitting at bolted connections.

Complete Structural Damage: Structure may have large permanent lateral displacement, may collapse or be in imminent danger of collapse due to failed shear walls, broken brace rods or failed framing connections; it may fall its foundations; large cracks in the foundations. Approximately 3% of the total area of W2 buildings with Complete damage is expected to be collapsed.

Steel Moment Frame (S1):

Slight Structural Damage: Minor deformations in connections or hairline cracks in few welds.

Moderate Structural Damage: Some steel members have yielded exhibiting observable permanent rotations at connections; few welded connections may exhibit major cracks through welds or few bolted connections may exhibit broken bolts or enlarged bolt holes.

Extensive Structural Damage: Most steel members have exceeded their yield capacity, resulting in significant permanent lateral deformation of the structure. Some of the structural members or connections may have exceeded their ultimate capacity exhibited by major permanent member rotations at connections, buckled flanges and failed connections. Partial collapse of portions of structure is possible due to failed critical elements and/or connections.

Complete Structural Damage: Significant portion of the structural elements have exceeded their ultimate capacities or some critical structural elements or connections have failed resulting in dangerous permanent lateral displacement, partial collapse or collapse of the building. Approximately 8%(low-rise), 5%(mid-rise) or 3%(high-rise) of the total area of S1 buildings with Complete damage is expected to be collapsed.

Steel Braced Frame (S2):

Slight Structural Damage: Few steel braces have yielded which may be indicated by minor stretching and/or buckling of slender brace members; minor cracks in welded connections; minor deformations in bolted brace connections.

Moderate Structural Damage: Some steel braces have yielded exhibiting observable stretching and/or buckling of braces; few braces, other members or connections have indications of reaching their ultimate capacity exhibited by buckled braces, cracked welds, or failed bolted connections.

Extensive Structural Damage: Most steel brace and other members have exceeded their yield capacity, resulting in significant permanent lateral deformation of the structure. Some structural members or connections have exceeded their ultimate capacity exhibited by buckled or broken braces, flange buckling, broken welds, or failed bolted connections. Anchor bolts at columns may be stretched. Partial collapse of portions of structure is possible due to failure of critical elements or connections.

Complete Structural Damage: Most the structural elements have reached their ultimate capacities or some critical members or connections have failed resulting in dangerous permanent lateral deflection, partial collapse or collapse of the building. Approximately 8%(low-rise), 5%(mid-rise) or 3%(high-rise) of the total area of S2 buildings with Complete damage is expected to be collapsed.

Steel Light Frame (S3):

These structures are mostly single story structures combining rod-braced frames in one direction and moment frames in the other. Due to repetitive nature of the structural systems, the type of damage to structural members is expected to be rather uniform throughout the structure.

Slight Structural Damage: Few steel rod braces have yielded which may be indicated by minor sagging of rod braces. Minor cracking at welded connections or minor deformations at bolted connections of moment frames may be observed.

Moderate Structural Damage: Most steel braces have yielded exhibiting observable significantly sagging rod braces; few brace connections may be broken. Some weld cracking may be observed in the moment frame connections.

Extensive Structural Damage: Significant permanent lateral deformation of the structure due to broken brace rods, stretched anchor bolts and permanent deformations at moment frame members. Some screw or welded attachments of roof and wall siding to steel framing may be broken. Some purlin and girt connections may be broken.

Complete Structural Damage: Structure is collapsed or in imminent danger of collapse due to broken rod bracing, failed anchor bolts or failed structural members or connections. Approximately 3% of the total area of S3 buildings with Complete damage is expected to be collapsed.

Steel Frame with Cast-In-Place Concrete Shear Walls (S4):

This is a "composite" structural system where primary lateral-force-resisting system is the concrete shear walls. Hence, slight, Moderate and Extensive damage states are likely to be determined by the shear walls while the collapse damage state would be determined by the failure of the structural frame.

Slight Structural Damage: Diagonal hairline cracks on most concrete shear wall surfaces; minor concrete spalling at few locations.

Moderate Structural Damage: Most shear wall surfaces exhibit diagonal cracks; some of the shear walls have exceeded their yield capacities exhibited by larger diagonal cracks and concrete spalling at wall ends.

Extensive Structural Damage: Most concrete shear walls have exceeded their yield capacities; few walls have reached or exceeded their ultimate capacity exhibited by large through-the wall diagonal cracks, extensive spalling around the cracks and visibly buckled wall reinforcement. Partial collapse may occur due to failed connections of steel framing to concrete walls. Some damage may be observed in steel frame connections.

Complete Structural Damage: Structure may be in danger of collapse or collapse due to total failure of shear walls and loss of stability of the steel frames. Approximately 8%(low-rise), 5%(mid-rise) or 3%(high-rise) of the total area of S4 buildings with Complete damage is expected to be collapsed.

Steel Frame with Unreinforced Masonry Infill Walls (S5):

This is a "composite" structural system where the initial lateral resistance is provided by the infill walls. Upon cracking of the infills, further lateral resistance is provided by the steel frames "braced" by the infill walls acting as diagonal compression struts. Collapse of the structure results when the infill walls disintegrate (due to compression failure of the masonry "struts") and the steel frame loses its stability.

Slight Structural Damage: Diagonal (sometimes horizontal) hairline cracks on most infill walls; cracks at frame-infill interfaces.

Moderate Structural Damage: Most infill wall surfaces exhibit larger diagonal or horizontal cracks; some walls exhibit crushing of brick around beam-column connections.

Extensive Structural Damage: Most infill walls exhibit large cracks; some bricks may be dislodged and fall; some infill walls may bulge out-of-plane; few walls may fall off partially or fully; some steel frame connections may have failed. Structure may exhibit permanent lateral deformation or partial collapse due to failure of some critical members.

Complete Structural Damage: Structure is collapsed or in danger of imminent collapse due to total failure of many infill walls and loss of stability of the steel frames. . Approximately 8%(low-rise), 5%(mid-rise) or 3%(high-rise) of the total area of S5 buildings with Complete damage is expected to be collapsed.

Reinforced Concrete Moment Resisting Frames (C1):

Slight Structural Damage: Flexural or shear type hairline cracks in some beams and columns near joints or within joints.

Moderate Structural Damage: Most beams and columns exhibit hairline cracks. In ductile frames some of the frame elements have reached yield capacity indicated by larger flexural cracks and some concrete spalling. Nonductile frames may exhibit larger shear cracks and spalling.

Extensive Structural Damage: Some of the frame elements have reached their ultimate capacity indicated in ductile frames by large flexural cracks, spalled concrete and buckled main reinforcement; nonductile frame elements may have suffered shear failures or bond failures at reinforcement splices, or broken ties or buckled main reinforcement in columns which may result in partial collapse.

Complete Structural Damage: Structure is collapsed or in imminent danger of collapse due to brittle failure of nonductile frame elements or loss of frame stability. Approximately 13%(low-rise), 10%(mid-rise) or 5%(high-rise) of the total area of C1 buildings with Complete damage is expected to be collapsed.

Concrete Shear Walls (C2):

Slight Structural Damage: Diagonal hairline cracks on most concrete shear wall surfaces; minor concrete spalling at few locations.

Moderate Structural Damage: Most shear wall surfaces exhibit diagonal cracks; some shear walls have exceeded yield capacity indicated by larger diagonal cracks and concrete spalling at wall ends.

Extensive Structural Damage: Most concrete shear walls have exceeded their yield capacities; some walls have exceeded their ultimate capacities indicated by large, through-the-wall diagonal cracks, extensive spalling around the cracks and visibly buckled wall reinforcement or rotation of narrow walls with inadequate foundations. Partial collapse may occur due to failure of nonductile columns not designed to resist lateral loads.

Complete Structural Damage: Structure has collapsed or is in imminent danger of collapse due to failure of most of the shear walls and failure of some critical beams or columns. Approximately 13%(low-rise), 10%(mid-rise) or 5%(high-rise) of the total area of C2 buildings with Complete damage is expected to be collapsed.

Concrete Frame Buildings with Unreinforced Masonry Infill Walls (C3):

This is a "composite" structural system where the initial lateral resistance is provided by the infill walls. Upon cracking of the infills, further lateral resistance is provided by the concrete frame "braced" by the infill acting as diagonal compression struts. Collapse of the structure results when the infill walls disintegrate (due to compression failure of the masonry "struts") and the frame loses stability, or when the concrete columns suffer shear failures due to reduced effective height and the high shear forces imposed on them by the masonry compression struts.

Slight Structural Damage: Diagonal (sometimes horizontal) hairline cracks on most infill walls; cracks at frame-infill interfaces.

Moderate Structural Damage: Most infill wall surfaces exhibit larger diagonal or horizontal cracks; some walls exhibit crushing of brick around beam-column connections. Diagonal shear cracks may be observed in concrete beams or columns.

Extensive Structural Damage: Most infill walls exhibit large cracks; some bricks may dislodge and fall; some infill walls may bulge out-of-plane; few walls may fall partially or fully; few concrete columns or beams may fail in shear resulting in partial collapse. Structure may exhibit permanent lateral deformation.

Complete Structural Damage: Structure has collapsed or is in imminent danger of collapse due to a combination of total failure of the infill walls and nonductile failure of the concrete beams and columns. Approximately 15%(low-rise), 13%(mid-rise) or 5%(high-rise) of the total area of C3 buildings with Complete damage is expected to be collapsed.

Precast Concrete Tilt-Up Walls (PC1):

Slight Structural Damage: Diagonal hairline cracks on concrete shear wall surfaces; larger cracks around door and window openings in walls with large proportion of openings; minor concrete spalling at few locations; minor separation of walls from the floor and roof diaphragms;

hairline cracks around metal connectors between wall panels and at connections of beams to walls.

Moderate Structural Damage: Most wall surfaces exhibit diagonal cracks; larger cracks in walls with door or window openings; few shear walls have exceeded their yield capacities indicated by larger diagonal cracks and concrete spalling. Cracks may appear at top of walls near panel intersections indicating “chord” yielding. Some walls may have visibly pulled away from the roof. Some welded panel connections may have been broken, indicated by spalled concrete around connections. Some spalling may be observed at the connections of beams to walls.

Extensive Structural Damage: In buildings with relatively large area of wall openings most concrete shear walls have exceeded their yield capacities and some have exceeded their ultimate capacities indicated by large, through-the-wall diagonal cracks, extensive spalling around the cracks and visibly buckled wall reinforcement. The plywood diaphragms may exhibit cracking and separation along plywood joints. Partial collapse of the roof may result from the failure of the wall-to-diaphragm anchorages sometimes with falling of wall panels.

Complete Structural Damage: Structure is collapsed or is in imminent danger of collapse due to failure of the wall-to-roof anchorages, splitting of ledgers, or failure of plywood-to-ledger nailing; failure of beams connections at walls; failure of roof or floor diaphragms; or, failure of the wall panels. Approximately 15% of the total area of PC1 buildings with Complete damage is expected to be collapsed.

Precast Concrete Frames with Concrete Shear Walls (PC2):

Slight Structural Damage: Diagonal hairline cracks on most shear wall surfaces; minor concrete spalling at few connections of precast members.

Moderate Structural Damage: Most shear wall surfaces exhibit diagonal cracks; some shear walls have exceeded their yield capacities indicated by larger cracks and concrete spalling at wall ends; observable distress or movement at connections of precast frame connections, some failures at metal inserts and welded connections.

Extensive Structural Damage: Most concrete shear walls have exceeded their yield capacities; some walls may have reached their ultimate capacities indicated by large, through-the wall diagonal cracks, extensive spalling around the cracks and visibly buckled wall reinforcement. Some critical precast frame connections may have failed resulting partial collapse.

Complete Structural Damage: Structure has collapsed or is in imminent danger of collapse due to failure of the shear walls and/or failures at precast frame connections. Approximately 15%(low-rise), 13%(mid-rise) or 10%(high-rise) of the total area of PC2 buildings with Complete damage is expected to be collapsed.

Reinforced Masonry Bearing Walls with Wood or Metal Deck Diaphragms (RM1):

Slight Structural Damage: Diagonal hairline cracks on masonry wall surfaces; larger cracks around door and window openings in walls with large proportion of openings; minor separation of walls from the floor and roof diaphragms.

Moderate Structural Damage: Most wall surfaces exhibit diagonal cracks; some of the shear walls have exceeded their yield capacities indicated by larger diagonal cracks. Some walls may have visibly pulled away from the roof.

Extensive Structural Damage: In buildings with relatively large area of wall openings most shear walls have exceeded their yield capacities and some of the walls have exceeded their ultimate capacities indicated by large, through-the-wall diagonal cracks and visibly buckled wall reinforcement. The plywood diaphragms may exhibit cracking and separation along plywood joints. Partial collapse of the roof may result from failure of the wall-to-diaphragm anchorages or the connections of beams to walls.

Complete Structural Damage: Structure has collapsed or is in imminent danger of collapse due to failure of the wall anchorages or due to failure of the wall panels. Approximately 13%(low-rise) or 10%(mid-rise) of the total area of RM1 buildings with Complete damage is expected to be collapsed.

Reinforced Masonry Bearing Walls with Precast Concrete Diaphragms (RM2):

Slight Structural Damage: Diagonal hairline cracks on masonry wall surfaces; larger cracks around door and window openings in walls with large proportion of openings.

Moderate Structural Damage: Most wall surfaces exhibit diagonal cracks; some of the shear walls have exceeded their yield capacities indicated by larger cracks.

Extensive Structural Damage: In buildings with relatively large area of wall openings most shear walls have exceeded their yield capacities and some of the walls have exceeded their ultimate capacities exhibited by large, through-the wall diagonal cracks and visibly buckled wall reinforcement. The diaphragms may also exhibit cracking

Complete Structural Damage: Structure is collapsed or is in imminent danger of collapse due to failure of the walls. Approximately 13%(low-rise), 10%(mid-rise) or 5%(high-rise) of the total area of RM2 buildings with Complete damage is expected to be collapsed.

Unreinforced Masonry Bearing Walls (URM):

Slight Structural Damage: Diagonal, stair-step hairline cracks on masonry wall surfaces; larger cracks around door and window openings in walls with large proportion of openings; movements of lintels; cracks at the base of parapets.

Moderate Structural Damage: Most wall surfaces exhibit diagonal cracks; some of the walls exhibit larger diagonal cracks; masonry walls may have visible separation from diaphragms; significant cracking of parapets; some masonry may fall from walls or parapets.

Extensive Structural Damage: In buildings with relatively large area of wall openings most walls have suffered extensive cracking. Some parapets and gable end walls have fallen. Beams or trusses may have moved relative to their supports.

Complete Structural Damage: Structure has collapsed or is in imminent danger of collapse due to in-plane or out-of-plane failure of the walls. Approximately 15% of the total area of URM buildings with Complete damage is expected to be collapsed.

Mobile Homes (MH):

Slight Structural Damage: Damage to some porches, stairs or other attached components.

Moderate Structural Damage: Major movement of the mobile home over its supports resulting in some damage to metal siding and stairs and requiring resetting of the mobile home on its supports.

Extensive Structural Damage: Mobile home has fallen partially off its supports, often severing utility lines.

Complete Structural Damage: Mobile home has totally fallen off its supports; usually severing utility lines, with steep jack stands penetrating through the floor. Approximately 3% of the total area of MH buildings with Complete damage is expected to be collapsed.

5.3.2 Nonstructural Damage

Four damage states are used to describe nonstructural damage: Slight, Moderate, Extensive and Complete nonstructural damage. Nonstructural damage is considered to be independent of the structural model building type (i.e. partitions, ceilings, cladding, etc. are assumed to incur the same damage when subjected to the same interstory drift or floor acceleration whether they are in a steel frame building or in a concrete shear wall building), consequently, building-specific damage state descriptions are not meaningful. Instead, general descriptions of nonstructural damage states are provided for common nonstructural systems.

Damage to drift-sensitive nonstructural components is primarily a function of interstory drift (e.g. full-height drywall partitions) while for acceleration-sensitive components (e.g. mechanical equipment) damage is a function of the floor acceleration. Developing fragility curves for each possible nonstructural component is not practicable for the purposes of regional loss estimation and there is insufficient data to develop such fragility curves. Hence, in this methodology nonstructural building components are grouped into drift-sensitive and acceleration-sensitive component groups, and the damage functions estimated for each group are assumed to be "typical" of it sub-components. Note, however, that damage depends on the anchorage/bracing provided to the nonstructural components. Damageability characteristics of each group are described by a set of fragility curves (see Subsection 5.4.3.3).

The type of nonstructural components in a given building is a function of the building occupancy-use classification. For example, single-family residences would not have curtain wall panels, suspended ceilings, elevators, etc. while these items would be found in an office building. Hence, the relative values of nonstructural components in relation to the overall building replacement value vary with type of occupancy. In Chapter 15, estimates of replacement cost breakdown between structural building components for different occupancy/use related classifications are provided; further breakdowns are provided by drift- and acceleration-sensitive nonstructural components.

In the following, general descriptions of the four nonstructural damage states are described for common nonstructural building components:

Partitions Walls

Slight Nonstructural Damage: A few cracks are observed at intersections of walls and ceilings and at corners of door openings.

Moderate Nonstructural Damage: Larger and more extensive cracks requiring repair and repainting; some partitions may require replacement of gypsum board or other finishes.

Extensive Nonstructural Damage: Most of the partitions are cracked and a significant portion may require replacement of finishes; some door frames in the partitions are also damaged and require re-setting.

Complete Nonstructural Damage: Most partition finish materials and framing may have to be removed and replaced; damaged studs repaired, and walls be refinished. Most door frames may also have to be repaired and replaced.

Suspended Ceilings

Slight Nonstructural Damage: A few ceiling tiles have moved or fallen down.

Moderate Nonstructural Damage: Falling of tiles is more extensive; in addition the ceiling support framing (T-bars) has disconnected and/or buckled at few locations; lenses have fallen off of some light fixtures and a few fixtures have fallen; localized repairs are necessary.

Extensive Nonstructural Damage: The ceiling system exhibits extensive buckling, disconnected t-bars and falling ceiling tiles; ceiling partially collapses at few locations and some light fixtures fall; repair typically involves removal of most or all ceiling tiles.

Complete Nonstructural Damage: The ceiling system is buckled throughout and/or fallen and requires complete replacement; many light fixtures fall.

Exterior Wall Panels

Slight Nonstructural Damage: Slight movement of the panels, requiring realignment.

Moderate Nonstructural Damage: The movements are more extensive; connections of panels to structural frame are damaged requiring further inspection and repairs; some window frames may need realignment

Extensive Nonstructural Damage: Most of the panels are cracked or otherwise damaged and misaligned, and most panel connections to the structural frame are damaged requiring thorough review and repairs; few panels fall or are in imminent danger of falling; some window panes are broken and some pieces of glass have fallen.

Complete Nonstructural Damage: Most panels are severely damaged, most connections are broken or severely damaged, some panels have fallen and most are in imminent danger of falling; extensive glass breakage and falling.

Electrical-Mechanical Equipment, Piping, Ducts

Slight Nonstructural Damage: The most vulnerable equipment (e.g. unanchored or on spring isolators) moves and damages attached piping or ducts.

Moderate Nonstructural Damage: Movements are larger and damage is more extensive; piping leaks at few locations; elevator machinery and rails may require realignment

Extensive Nonstructural Damage: Equipment on spring isolators topples and falls; other unanchored equipment slides or falls breaking connections to piping and ducts; leaks develop at many locations; anchored equipment indicate stretched bolts or strain at anchorages.

Complete Nonstructural Damage: Equipment is damaged by sliding, overturning or failure of their supports and is not operable; piping is leaking at many locations; some pipe and duct supports have failed causing pipes and ducts to fall or hang down; elevator rails are buckled or have broken supports and/or counterweights have derailed.

5.4 Building Damage Due to Ground Shaking

5.4.1 Overview

This section describes capacity and fragility curves used in the Methodology to estimate the probability of Slight, Moderate, Extensive and Complete damage to general building stocks. General building stock represents a population of a given model building type designed to either High-Code, Moderate-Code, or Low-Code seismic standards, or not seismically designed, referred to as to a Pre-Code buildings. Chapter 6 describes Special building damage functions for estimating damage to hospitals and other essential facilities that are designed and constructed to above average seismic standards.

Capacity curves and fragility curves for High-Code, Moderate-Code, Low-Code and Pre-Code buildings are based on modern code (e.g., 1976 *Uniform Building Code*, 1985 *NEHRP Provisions*, or later editions of these model codes). Design criteria for various seismic design zones, as shown in Table 5.3. Additional description of seismic levels may be found in Section 5.7.

Table 5.3 Approximate Basis for Seismic Design Levels

Seismic Design Level	Seismic Zone (*Uniform Building Code*)	Map Area (*NEHRP Provisions*)
High-Code	4	7
Moderate-Code	2B	5
Low-Code	1	3
Pre-Code	0	1

The capacity and fragility curves represent buildings designed and constructed to modern seismic code provisions. Study areas (e.g., census tracts) of recent construction are appropriately modeled using building damage functions with a seismic design level that corresponds to the seismic zone or map area of the governing provisions. Older areas of construction, not conforming to modern standards, should be modeled using a lower level of seismic design. For example, in areas of high seismicity (e.g., coastal California), buildings of newer construction (e.g., post-1973) are best represented by High-Code damage functions, while buildings of older construction would be best represented by Moderate-Code damage functions, if built after about 1940, or by Pre-Code damage functions, if built before about 1940 (i.e., before seismic codes existed). Pre-Code damage functions are appropriate for modeling older buildings that were not designed for earthquake load, regardless of where they are located in the United States. Guidance is provided to expert users in Section 5.7 for selection of appropriate building damage functions

5.4.2 Capacity Curves

Most buildings are presently designed or evaluated using linear-elastic analysis methods, primarily due to the relative simplicity of these methods in comparison to more complex, nonlinear methods. Typically, building response is based on linear-elastic properties of the structure and forces corresponding to the design-basis earthquake. For design of building elements, linear-elastic (5%-damped) response is reduced by a factor (e.g. the "R-Factor" in 1994 *NEHRP Provisions*) that varies for different types of lateral force resisting systems. The reduction factor is based on empirical data and judgment that account for the inelastic deformation capability (ductility) of the structural system, redundancy, overstrength, increased damping (above 5% of critical) at large deformations, and other factors that influence building capacity. Although this "force-based" approach is difficult to justify by rational engineering analysis, buildings designed using these methods have performed reasonably well in past earthquakes. Aspects of these methods found not to work well in earthquakes have been studied and improved. In most cases, building capacity has been increased by improvements to detailing practices (e.g., better confinement of steel reinforcement in concrete elements).

Except for a few brittle systems and acceleration-sensitive elements, building damage is primarily a function of building displacement, rather than force. In the inelastic range of building response, increasingly larger damage would result from increased building displacement although lateral force would remain constant or decrease. Hence, successful prediction of earthquake damage to buildings requires reasonably accurate estimation of building displacement response in the inelastic range. This, however, can not be accomplished using linear-elastic methods, since the buildings respond inelastically to earthquake ground shaking of magnitudes of interest for damage prediction. Building capacity (push-over) curves, used with capacity spectrum method (CSM) techniques [Mahaney, et. al., 1993, Kircher, 1996], provide simple and reasonably accurate means of predicting inelastic building displacement response for damage estimation purposes.

A building capacity curve (also known as a push-over curve) is a plot of a building's lateral load resistance as a function of a characteristic lateral displacement (i.e., a force-deflection plot). It is derived from a plot of static-equivalent base shear versus building (e.g., roof) displacement. In order to facilitate direct comparison with earthquake demand (i.e. overlaying the capacity curve with a response spectrum), the force (base shear) axis is converted to spectral acceleration and the displacement axis is converted to spectral displacement. Such a plot provides an estimate of the building's "true" deflection (displacement response) for any given earthquake response spectrum.

The building capacity curves developed for the Methodology are based on engineering design parameters and judgment. Three control points that define model building capacity describe each curve:

- Design Capacity
- Yield Capacity
- Ultimate Capacity

Design capacity represents the nominal building strength required by current model seismic code provisions (e.g., 1994 *NEHRP Provisions*) or an estimate of the nominal strength for buildings not designed for earthquake loads. Wind design is not considered in the estimation of design capacity, and certain buildings (e.g., tall buildings located in zones of low or moderate seismicity) may have a lateral design strength considerably greater than that based on seismic code provisions.

Yield capacity represents the true lateral strength of the building considering redundancies in design, conservatism in code requirements and true (rather than nominal) strength of materials. Ultimate capacity represents the maximum strength of the building when the global structural system has reached a fully plastic state. Ultimate capacity implicitly accounts for loss of strength due to shear failure of brittle elements. Typically, buildings are assumed capable of deforming beyond their ultimate point without loss of stability, but their structural system provides no additional resistance to lateral earthquake force.

Up to the yield point, the building capacity curve is assumed to be linear with stiffness based on an estimate of the true period of the building. The true period is typically longer than the code-specified period of the building due to flexing of diaphragms of short, stiff buildings, flexural cracking of elements of concrete and masonry structures, flexibility of foundations and other factors observed to affect building stiffness. From the yield point to the ultimate point, the capacity curve transitions in slope from an essentially elastic state to a fully plastic state. The capacity curve is assumed to remain plastic past the ultimate point. An example building capacity curve is shown in Figure 5.3.

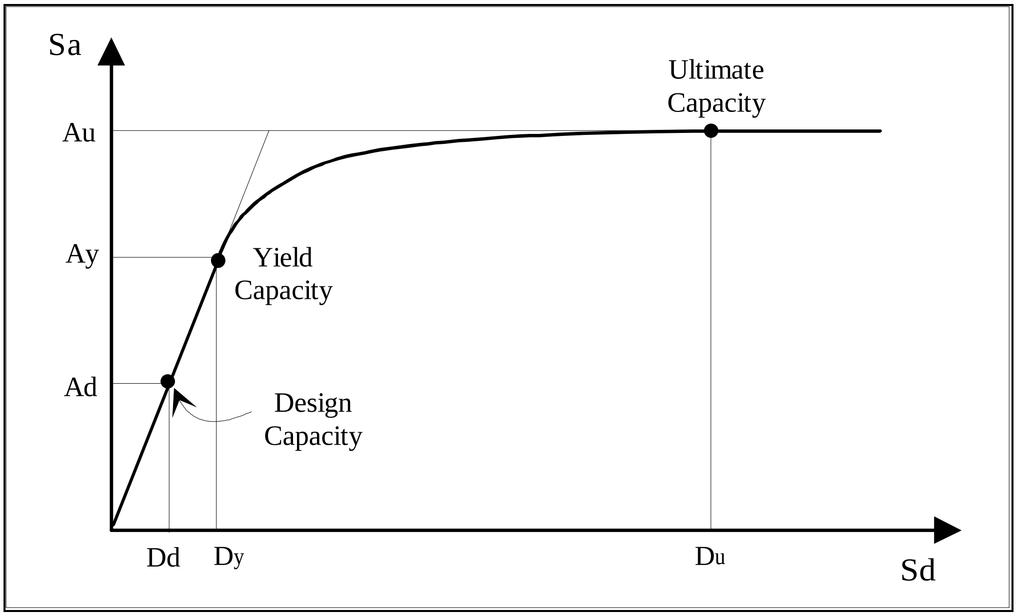


Figure 5.3 Example Building Capacity Curve.

The building capacity curves are constructed based on estimates of engineering properties that affect the design, yield and ultimate capacities of each model building type. These properties are defined by the following parameters:

C_s	design strength coefficient (fraction of building's weight),
T_e	true "elastic" fundamental-mode period of building (seconds),
α_1	fraction of building weight effective in push-over mode,
α_2	fraction of building height at location of push-over mode displacement,
γ	"overstrength" factor relating "true" yield strength to design strength,
λ	"overstrength" factor relating ultimate strength to yield strength, and
μ	"ductility" factor relating ultimate displacement to λ times the yield displacement (i.e., assumed point of significant yielding of the structure)

The design strength, C_s, is approximately based, on the lateral-force design requirements of current seismic codes (e.g., *1994 NEHRP Provisions*). These requirements are a function of the building's seismic zone location and other factors including: site soil condition, type of lateral-force-resisting system and building period. For each of the four design levels (High-Code, Moderate-Code, Low-Code and Pre-Code), design capacity is based on the best estimate of typical design properties. Table 5.4 summarizes design capacity for each building type and design level. Building period, T_e, push-over mode parameters α_1 and α_2, the ratio of yield to design strength, γ, and the ratio of ultimate to yield strength, λ, are assumed to be independent of design level. Values of these parameters are summarized in Table 5.5 for each building type. Values of the "ductility" factor, μ, are given in Table 5.6 for each building type and design level. Note that for the following tables, shaded boxes indicate types that are not permitted by current seismic codes.

Table 5.4 Code Building Capacity Parameters - Design Strength (C_s)

Building Type	Seismic Design Level (Fraction of Building Weight)			
	High-Code	Moderate-Code	Low-Code	Pre-Code
W1	0.200	0.150	0.100	0.100
W2	0.200	0.100	0.050	0.050
S1L	0.133	0.067	0.033	0.033
S1M	0.100	0.050	0.025	0.025
S1H	0.067	0.033	0.017	0.017
S2L	0.200	0.100	0.050	0.050
S2M	0.200	0.100	0.050	0.050
S2H	0.150	0.075	0.038	0.038
S3	0.200	0.100	0.050	0.050
S4L	0.160	0.080	0.040	0.040
S4M	0.160	0.080	0.040	0.040
S4H	0.120	0.060	0.030	0.030
S5L			0.050	0.050
S5M			0.050	0.050
S5H			0.038	0.038
C1L	0.133	0.067	0.033	0.033
C1M	0.133	0.067	0.033	0.033
C1H	0.067	0.033	0.017	0.017
C2L	0.200	0.100	0.050	0.050
C2M	0.200	0.100	0.050	0.050
C2H	0.150	0.075	0.038	0.038
C3L			0.050	0.050
C3M			0.050	0.050
C3H			0.038	0.038
PC1	0.200	0.100	0.050	0.050
PC2L	0.200	0.100	0.050	0.050
PC2M	0.200	0.100	0.050	0.050
PC2H	0.150	0.075	0.038	0.038
RM1L	0.267	0.133	0.067	0.067
RM1M	0.267	0.133	0.067	0.067
RM2L	0.267	0.133	0.067	0.067
RM2M	0.267	0.133	0.067	0.067
RM2H	0.200	0.100	0.050	0.050
URML			0.067	0.067
URMM			0.067	0.067
MH	0.100	0.100	0.100	0.100

Table 5.5 Code Building Capacity Parameters - Period (T_e), Pushover Mode

Response Factors (α_1, α_2) and Overstrength Ratios (γ, λ)

Building Type	Height to Roof (Feet)	Period, T_e (Seconds)	Modal Factors		Overstrength Ratios	
			Weight, α_1	Height, α_2	Yield, γ	Ultimate, λ
W1	14.0	0.35	0.75	0.75	1.50	3.00
W2	24.0	0.40	0.75	0.75	1.50	2.50
S1L	24.0	0.50	0.80	0.75	1.50	3.00
S1M	60.0	1.08	0.80	0.75	1.25	3.00
S1H	156.0	2.21	0.75	0.60	1.10	3.00
S2L	24.0	0.40	0.75	0.75	1.50	2.00
S2M	60.0	0.86	0.75	0.75	1.25	2.00
S2H	156.0	1.77	0.65	0.60	1.10	2.00
S3	15.0	0.40	0.75	0.75	1.50	2.00
S4L	24.0	0.35	0.75	0.75	1.50	2.25
S4M	60.0	0.65	0.75	0.75	1.25	2.25
S4H	156.0	1.32	0.65	0.60	1.10	2.25
S5L	24.0	0.35	0.75	0.75	1.50	2.00
S5M	60.0	0.65	0.75	0.75	1.25	2.00
S5H	156.0	1.32	0.65	0.60	1.10	2.00
C1L	20.0	0.40	0.80	0.75	1.50	3.00
C1M	50.0	0.75	0.80	0.75	1.25	3.00
C1H	120.0	1.45	0.75	0.60	1.10	3.00
C2L	20.0	0.35	0.75	0.75	1.50	2.50
C2M	50.0	0.56	0.75	0.75	1.25	2.50
C2H	120.0	1.09	0.65	0.60	1.10	2.50
C3L	20.0	0.35	0.75	0.75	1.50	2.25
C3M	50.0	0.56	0.75	0.75	1.25	2.25
C3H	120.0	1.09	0.65	0.60	1.10	2.25
PC1	15.0	0.35	0.50	0.75	1.50	2.00
PC2L	20.0	0.35	0.75	0.75	1.50	2.00
PC2M	50.0	0.56	0.75	0.75	1.25	2.00
PC2H	120.0	1.09	0.65	0.60	1.10	2.00
RM1L	20.0	0.35	0.75	0.75	1.50	2.00
RM1M	50.0	0.56	0.75	0.75	1.25	2.00
RM2L	20.0	0.35	0.75	0.75	1.50	2.00
RM2M	50.0	0.56	0.75	0.75	1.25	2.00
RM2H	120.0	1.09	0.65	0.60	1.10	2.00
URML	15.0	0.35	0.50	0.75	1.50	2.00
URMM	35.0	0.50	0.75	0.75	1.25	2.00
MH	10.0	0.35	1.00	1.00	1.50	2.00

Table 5.6 Code Building Capacity Parameter - Ductility (μ)

Building Type	Seismic Design Level			
	High-Code	Moderate-Code	Low-Code	Pre-Code
W1	8.0	6.0	6.0	6.0
W2	8.0	6.0	6.0	6.0
S1L	8.0	6.0	5.0	5.0
S1M	5.3	4.0	3.3	3.3
S1H	4.0	3.0	2.5	2.5
S2L	8.0	6.0	5.0	5.0
S2M	5.3	4.0	3.3	3.3
S2H	4.0	3.0	2.5	2.5
S3	8.0	6.0	5.0	5.0
S4L	8.0	6.0	5.0	5.0
S4M	5.3	4.0	3.3	3.3
S4H	4.0	3.0	2.5	2.5
S5L			5.0	5.0
S5M			3.3	3.3
S5H			2.5	2.5
C1L	8.0	6.0	5.0	5.0
C1M	5.3	4.0	3.3	3.3
C1H	4.0	3.0	2.5	2.5
C2L	8.0	6.0	5.0	5.0
C2M	5.3	4.0	3.3	3.3
C2H	4.0	3.0	2.5	2.5
C3L			5.0	5.0
C3M			3.3	3.3
C3H			2.5	2.5
PC1	8.0	6.0	5.0	5.0
PC2L	8.0	6.0	5.0	5.0
PC2M	5.3	4.0	3.3	3.3
PC2H	4.0	3.0	2.5	2.5
RM1L	8.0	6.0	5.0	5.0
RM1M	5.3	4.0	3.3	3.3
RM2L	8.0	6.0	5.0	5.0
RM2M	5.3	4.0	3.3	3.3
RM2H	4.0	3.0	2.5	2.5
URML			5.0	5.0
URMM			3.3	3.3
MH	6.0	6.0	6.0	6.0

Building capacity curves are assumed to have a range of possible properties that are lognormally distributed as a function of the ultimate strength (A_u) of each capacity curve. Capacity curves described by the values of parameters given in Tables 5.4, 5.5 and 5.6 represent median estimates of building capacity. The variability of the capacity of each building type is assumed to be: $\beta(A_u) = 0.25$ for code-designed buildings (High-Code, Moderate-Code and Low-Code seismic design levels) and $\beta(A_u) = 0.30$ for Pre-Code buildings.

Example construction of median, 84th percentile (+1β) and 16th percentile (-1β) building capacity curves for a typical building is illustrated in Figure 5.4. Median capacity curves are intersected with demand spectra to estimate peak building response. The variability of the capacity curves is used, with other sources of variability and uncertainty, to define total fragility curve variability.

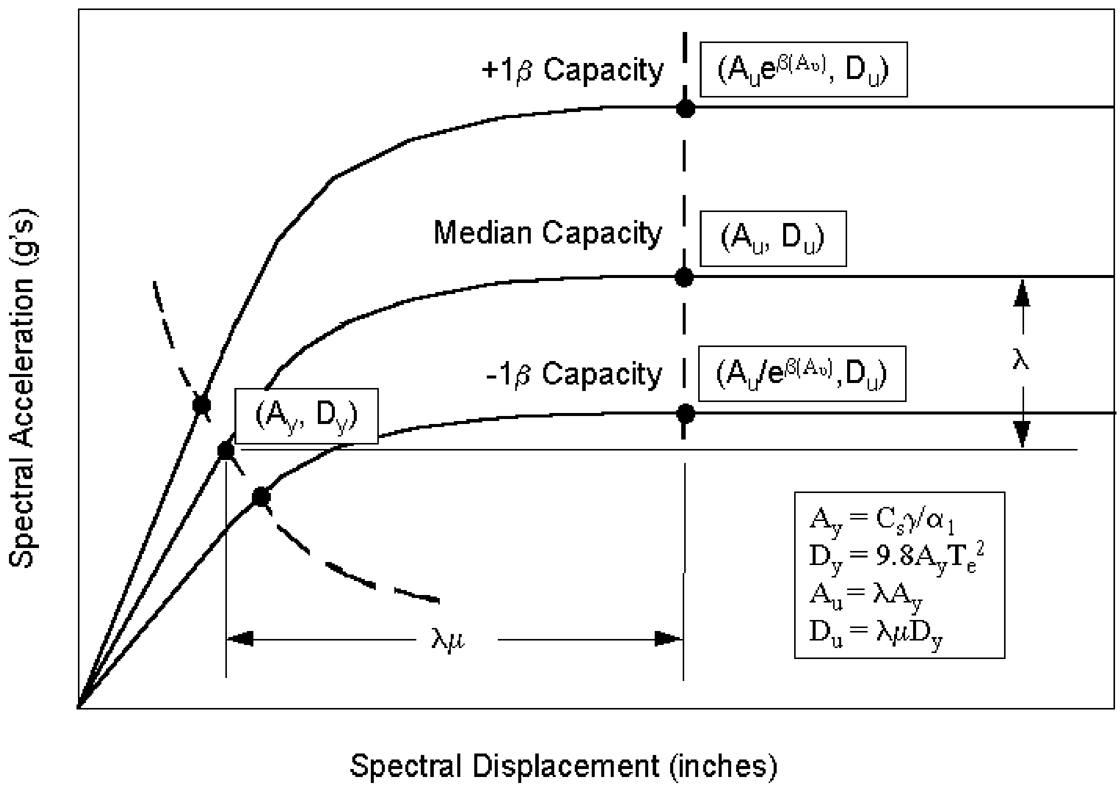


Figure 5.4 Example Construction of Median, +1β and -1β Building Capacity Curves.

Tables 5.7a, 5.7b, 5.7c and 5.7d summarize yield capacity and ultimate capacity control points for High-Code, Moderate-Code, Low-Code and Pre-Code seismic design levels, respectively. Note that for the following tables, shaded boxes indicate types that are not permitted by current seismic codes.

Table 5.7a Code Building Capacity Curves - High-Code Seismic Design Level

Building Type	Yield Capacity Point		Ultimate Capacity Point	
	D_y (in.)	A_y (g)	D_u (in.)	A_u (g)
W1	0.48	0.400	11.51	1.200
W2	0.63	0.400	12.53	1.000
S1L	0.61	0.250	14.67	0.749
S1M	1.78	0.156	28.40	0.468
S1H	4.66	0.098	55.88	0.293
S2L	0.63	0.400	10.02	0.800
S2M	2.43	0.333	25.88	0.667
S2H	7.75	0.254	61.97	0.508
S3	0.63	0.400	10.02	0.800
S4L	0.38	0.320	6.91	0.720
S4M	1.09	0.267	13.10	0.600
S4H	3.49	0.203	31.37	0.457
S5L				
S5M				
S5H				
C1L	0.39	0.250	9.39	0.749
C1M	1.15	0.208	18.44	0.624
C1H	2.01	0.098	24.13	0.293
C2L	0.48	0.400	9.59	1.000
C2M	1.04	0.333	13.84	0.833
C2H	2.94	0.254	29.39	0.635
C3L				
C3M				
C3H				
PC1	0.72	0.600	11.51	1.200
PC2L	0.48	0.400	7.67	0.800
PC2M	1.04	0.333	11.07	0.667
PC2H	2.94	0.254	23.52	0.508
RM1L	0.64	0.533	10.23	1.066
RM1M	1.38	0.444	14.76	0.889
RM2L	0.64	0.533	10.23	1.066
RM2M	1.38	0.444	14.76	0.889
RM2H	3.92	0.338	31.35	0.677
URML				
URMM				
MH	0.18	0.150	2.16	0.300

Table 5.7b Code Building Capacity Curves - Moderate-Code Seismic Design Level

Building Type	Yield Capacity Point		Ultimate Capacity Point	
	D_y (in.)	A_y (g)	D_u (in.)	A_u (g)
W1	0.36	0.300	6.48	0.900
W2	0.31	0.200	4.70	0.500
S1L	0.31	0.125	5.50	0.375
S1M	0.89	0.078	10.65	0.234
S1H	2.33	0.049	20.96	0.147
S2L	0.31	0.200	3.76	0.400
S2M	1.21	0.167	9.70	0.333
S2H	3.87	0.127	23.24	0.254
S3	0.31	0.200	3.76	0.400
S4L	0.19	0.160	2.59	0.360
S4M	0.55	0.133	4.91	0.300
S4H	1.74	0.102	11.76	0.228
S5L				
S5M				
S5H				
C1L	0.20	0.125	3.52	0.375
C1M	0.58	0.104	6.91	0.312
C1H	1.01	0.049	9.05	0.147
C2L	0.24	0.200	3.60	0.500
C2M	0.52	0.167	5.19	0.417
C2H	1.47	0.127	11.02	0.317
C3L				
C3M				
C3H				
PC1	0.36	0.300	4.32	0.600
PC2L	0.24	0.200	2.88	0.400
PC2M	0.52	0.167	4.15	0.333
PC2H	1.47	0.127	8.82	0.254
RM1L	0.32	0.267	3.84	0.533
RM1M	0.69	0.222	5.54	0.444
RM2L	0.32	0.267	3.84	0.533
RM2M	0.69	0.222	5.54	0.444
RM2H	1.96	0.169	11.76	0.338
URML				
URMM				
MH	0.18	0.150	2.16	0.300

Table 5.7c Code Building Capacity Curves - Low-Code Seismic Design Level

Building Type	Yield Capacity Point		Ultimate Capacity Point	
	D_y (in.)	A_y (g)	D_u (in.)	A_u (g)
W1	0.24	0.200	4.32	0.600
W2	0.16	0.100	2.35	0.250
S1L	0.15	0.062	2.29	0.187
S1M	0.44	0.039	4.44	0.117
S1H	1.16	0.024	8.73	0.073
S2L	0.16	0.100	1.57	0.200
S2M	0.61	0.083	4.04	0.167
S2H	1.94	0.063	9.68	0.127
S3	0.16	0.100	1.57	0.200
S4L	0.10	0.080	1.08	0.180
S4M	0.27	0.067	2.05	0.150
S4H	0.87	0.051	4.90	0.114
S5L	0.12	0.100	1.20	0.200
S5M	0.34	0.083	2.27	0.167
S5H	1.09	0.063	5.45	0.127
C1L	0.10	0.062	1.47	0.187
C1M	0.29	0.052	2.88	0.156
C1H	0.50	0.024	3.77	0.073
C2L	0.12	0.100	1.50	0.250
C2M	0.26	0.083	2.16	0.208
C2H	0.74	0.063	4.59	0.159
C3L	0.12	0.100	1.35	0.225
C3M	0.26	0.083	1.95	0.188
C3H	0.74	0.063	4.13	0.143
PC1	0.18	0.150	1.80	0.300
PC2L	0.12	0.100	1.20	0.200
PC2M	0.26	0.083	1.73	0.167
PC2H	0.74	0.063	3.67	0.127
RM1L	0.16	0.133	1.60	0.267
RM1M	0.35	0.111	2.31	0.222
RM2L	0.16	0.133	1.60	0.267
RM2M	0.35	0.111	2.31	0.222
RM2H	0.98	0.085	4.90	0.169
URML	0.24	0.200	2.40	0.400
URMM	0.27	0.111	1.81	0.222
MH	0.18	0.150	2.16	0.300

Table 5.7d Building Capacity Curves - Pre-Code Seismic Design Level

Building Type	Yield Capacity Point		Ultimate Capacity Point	
	D_y (in.)	A_y (g)	D_u (in.)	A_u (g)
W1	0.24	0.200	4.32	0.600
W2	0.16	0.100	2.35	0.250
S1L	0.15	0.062	2.75	0.187
S1M	0.44	0.039	5.33	0.117
S1H	1.16	0.024	10.48	0.073
S2L	0.16	0.100	1.88	0.200
S2M	0.61	0.083	4.85	0.167
S2H	1.94	0.063	11.62	0.127
S3	0.16	0.100	1.88	0.200
S4L	0.10	0.080	1.30	0.180
S4M	0.27	0.067	2.46	0.150
S4H	0.87	0.051	5.88	0.114
S5L	0.12	0.100	1.20	0.200
S5M	0.34	0.083	2.27	0.167
S5H	1.09	0.063	5.45	0.127
C1L	0.10	0.062	1.76	0.187
C1M	0.29	0.052	3.46	0.156
C1H	0.50	0.024	4.52	0.073
C2L	0.12	0.100	1.80	0.250
C2M	0.26	0.083	2.60	0.208
C2H	0.74	0.063	5.51	0.159
C3L	0.12	0.100	1.35	0.225
C3M	0.26	0.083	1.95	0.188
C3H	0.74	0.063	4.13	0.143
PC1	0.18	0.150	2.16	0.300
PC2L	0.12	0.100	1.44	0.200
PC2M	0.26	0.083	2.08	0.167
PC2H	0.74	0.063	4.41	0.127
RM1L	0.16	0.133	1.92	0.267
RM1M	0.35	0.111	2.77	0.222
RM2L	0.16	0.133	1.92	0.267
RM2M	0.35	0.111	2.77	0.222
RM2H	0.98	0.085	5.88	0.169
URML	0.24	0.200	2.40	0.400
URMM	0.27	0.111	1.81	0.222
MH	0.18	0.150	2.16	0.300

5.4.3 Fragility Curves

This section describes building fragility curves for Slight, Moderate, Extensive and Complete structural damage states and Slight, Moderate, Extensive and Complete nonstructural damage states. Each fragility curve is characterized by median and lognormal standard deviation (β) values of PESH demand. Spectral displacement is the PESH parameter used for structural damage and nonstructural damage to drift-sensitive components. Spectral acceleration is the PESH parameter used for calculating nonstructural damage to acceleration-sensitive components.

5.4.3.1 Background

The probability of being in or exceeding a given damage state is modeled as a cumulative lognormal distribution. For structural damage, given the spectral displacement, $S_{d,}$ the probability of being in or exceeding a damage state, ds, is modeled as:

$$P\left[ds \middle| S_d\right] = \Phi\left[\frac{1}{\beta_{ds}} \ln\left(\frac{S_d}{\overline{S}_{d,ds}}\right)\right] \quad (5\text{-}3)$$

where: $\overline{S}_{d,ds}$ is the median value of spectral displacement at which the building reaches the threshold of the damage state, ds,

β_{ds} is the standard deviation of the natural logarithm of spectral displacement of damage state, ds, and

Φ is the standard normal cumulative distribution function.

For example, a mid-rise, concrete-frame building (C1M) of High-Code seismic design has Extensive structural damage defined by a median spectral displacement value ($\overline{S}_{d,E}$) of 9.0 inches and a lognormal standard deviation value (β_E) of 0.68. The lognormal fragility curve for Extensive structural damage to this building is shown in Figure 5.5.

In Figure 5.5, the symbol, $\overline{S}$, indicates the median value of 9.0 inches. The symbol, S_+, indicates the +1 lognormal standard deviation level of the fragility curve, which is evaluated as $S_+ = \overline{S}$ x exp(β) = 17.8 inches. Similarly, the symbol, S_-, indicates the -1 lognormal standard deviation level of the fragility curve, which is evaluated as $S_- = \bar{S}/\exp(\beta)$ = 4.6 inches. The corresponding probabilities of being in or exceeding the Extensive damage state for this example are:

$$P\left[\text{Extensive}\cdot\text{Damage}\middle|S_d = S_- = 4.6\ \text{inches}\right] = 0.16$$

$$P\left[\text{Extensive}\cdot\text{Damage}\middle|S_d = \bar{S} = 9.0\ \text{inches}\right] = 0.50$$

$$P\left[\text{Extensive}\cdot\text{Damage}\middle|S_d = S_+ = 17.8\ \text{inches}\right] = 0.84$$

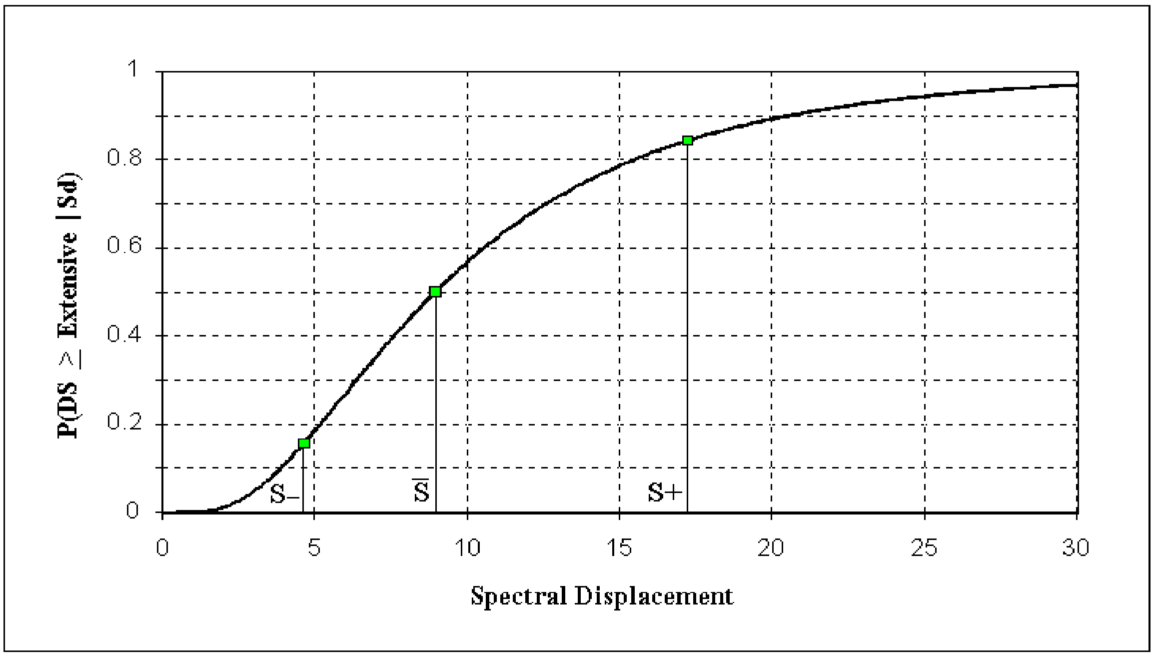


Figure 5.5 Example Fragility Curve - Extensive Structural Damage,

C1M Model Building Type, High-Code Seismic Design.

5.4.3.2 Development of Damage State Medians

Median values of fragility curves are developed for each damage states (i.e., Slight, Moderate, Extensive and Complete) and for each of the three types of building components: structural, nonstructural drift-sensitive and nonstructural acceleration-sensitive components. Structural fragility is characterized in terms of spectral displacement and by equivalent-PGA fragility curves (for buildings that are components of lifelines). Section 5.4.4 describes development of median values of equivalent-PGA structural fragility curves based on the structural fragility curves of this section.

Median values of structural component fragility are based on building drift ratios that describe the threshold of damage states. Damage-state drift ratios are converted to spectral displacement using Equation (5-4):

$$\overline{S}_{d,Sds} = \delta_{R,Sds} \cdot \alpha_2 \cdot h \tag{5-4}$$

where: $\overline{S}_{d,Sds}$ is the median value of spectral displacement, in inches, of structural components for damage state, ds,

$\delta_{R,Sds}$ is the drift ratio at the threshold of structural damage state, ds,

α_2 is the fraction of the building (roof) height at the location of push-over mode displacement, as specified in Table 5.5, and

h is the typical roof height, in inches, of the model building type of interest (see Table 5.1 for typical building height).

Values of damage-state drift ratios are included in the Methodology based, in part, on a study by OAK Engineering [OAK, 1994] that reviewed and synthesized available drift/damage information from a number of published sources, including Kustu et al. (1982), Ferritto (1982 and 1983), Czarnecki (1973), Hasselman et al. (1980), Whitman et al. (1977) and Wong (1975).

Median values of nonstructural drift-sensitive component fragility are based on building drift ratios that describe the threshold of damage states. Nonstructural drift-sensitive components are identified in Table 5.2. Damage state drift ratios for nonstructural drift-sensitive components are converted to median values of spectral displacement using the same approach as that of Equation (5-4). Values of damage-state drift are based, in part, on the work of Ferrito (1982 and 1983) and on a recent update of this data included in a California Division of the State Architect report [DSA, 1996].

Median values of nonstructural acceleration-sensitive component fragility are based on peak floor (input) acceleration that describes the threshold of damage states. These values of acceleration are used directly as median values of spectral acceleration for nonstructural acceleration-sensitive component fragility curves. Values of damage-state acceleration are based, in part, on the work of Ferrito (1982 and 1983) and on a recent update of this data included in a California Division of the State Architect report [DSA, 1996].

5.4.3.3 Development of Damage State Variability

Lognormal standard deviation (β) values that describe the variability of fragility curves are developed for each damage states (i.e., Slight, Moderate, Extensive and Complete) and for each of the three types of building components: structural, nonstructural drift-sensitive and nonstructural acceleration-sensitive components. Structural fragility is characterized in terms of spectral displacement and by equivalent-PGA fragility curves (for buildings that are components of lifelines). Section 5.4.4 describes development of variability values for equivalent-PGA structural fragility curves.

The total variability of each structural damage state, β_{Sds}, is modeled by the combination of three contributors to structural damage variability, β_C, β_D and $\beta_{M(Sds)}$, as described in Equation (5-5):

$$\beta_{Sds} = \sqrt{\left(\mathrm{CONV}\left[\beta_C, \beta_D, \overline{S}_{d,Sds}\right]\right)^2 + \left(\beta_{M(Sds)}\right)^2} \tag{5-5}$$

where:

β_{Sds} is the lognormal standard deviation that describes the total variability for structural damage state, ds,

β_C is the lognormal standard deviation parameter that describes the variability of the capacity curve,

β_D is the lognormal standard deviation parameter that describes the variability of the demand spectrum,

$\beta_{M(Sds)}$ is the lognormal standard deviation parameter that describes the uncertainty in the estimate of the median value of the threshold of structural damage state, ds.

The variability of building response depends jointly on demand and capacity (since capacity curves are nonlinear). The function “CONV” in Equation (5-5) implies a complex process of convolving probability distributions of the demand spectrum and the capacity curve, respectively. Demand spectra and capacity curves are described probabilistically by median properties and variability parameters, β_D and β_C, respectively. Capacity curves are defined for each building type, but the demand spectrum is based on the PESH input spectrum whose shape is a function of source/site conditions. For development of building fragility curves, the demand spectrum shape represented Moderate duration ground shaking of a large-magnitude WUS earthquake at a soil site.

The convolution process produces a surface that describes the probability of each demand/capacity intersection point when the median demand spectrum is scaled to intersect the median capacity curve at a given amplitude of response. Discrete values of the probabilistic surface are summed along a line anchored to the damage state median of interest (e.g., $S_{d,Sds}$) to estimate the probability of reaching or exceeding the median value given building response at the intersection point. This process is repeated for other intersection points to form a cumulative description of the probability of reaching (or exceeding) the damage state of interest. A lognormal function is fit to this cumulative curve yielding an estimate of the lognormal standard deviation of the combined effect of demand and capacity variability on building fragility.

The lognormal standard deviation parameter that describes the uncertainty in the estimate of the median value of the threshold of structural damage state ds, $\beta_{M(Sds)}$, is assumed to be independent of capacity and demand, and is added by the square-root-sum-of-the-squares (SRSS) method to the lognormal standard deviation parameter representing the combined effects of demand and capacity variability.

In the development of the damage state variability for implementation with the USGS probabilistic seismic hazard curves, the procedure was modified. The USGS explicitly incorporated the ground motion uncertainty in their Project 97 seismic hazard curves. (See Chapter 4) These hazard curves were the basis for the **Hazus** PESH data used in the Methodology’s probabilistic analysis procedure. To avoid overestimation of the damage state variability due to this double counting of ground motion uncertainty, the convolution process was modified and reanalyzed. Modified damage state variability parameters were developed for each probabilistic return period (a total of 8 return periods) and used when the probabilistic analysis option is selected. Due to large amount of modified parameters, their values are not reproduced in this chapter. To review the modified parameters, the user can access them via the **Hazus** software [**Analysis-Damage Functions-Buildings**].

The process, described above for structural components, is the same approach used to estimate the lognormal standard deviation for nonstructural drift-sensitive components. Nonstructural acceleration-sensitive components are treated in a similar manner to nonstructural drift-sensitive components, except that cumulative descriptions of the probability of reaching (or exceeding) the damage state of interest are developed in terms of spectral acceleration (rather than spectra displacement). Also, nonstructural acceleration-sensitive components are divided into two sub-populations: (1) components at or near ground level and (2) components at upper floors or on the roof. PGA, rather than spectral acceleration, is a more appropriate PESH input for components at or near ground level. Fragility curves for nonstructural acceleration-sensitive components assume 50% (low-rise), 33% (mid-rise) or 20% (high-rise) of nonstructural components are located at, or near, the ground floor, and represent a weighted combination of the probability of damage to components located at, or near, ground level and components located at upper-floor levels of the building.

5.4.3.4 Structural Damage

Structural damage fragility curves for buildings are described by median values of drift that define the thresholds of Slight, Moderate, Extensive and Complete damage states. In general, these estimates of drift are different for each model building type (including height) and seismic design level. Table 5.8 summarizes the ranges of drift ratios used to define structural damage for various low-rise building types designed to current High-Code seismic provisions. A complete listing of damage-state drift ratios for all building types and heights are provided for each seismic design level in Tables 5.9a, 5.9b, 5.9c and 5.9d, respectively.

Table 5.8 Typical Drift Ratios Used to Define Median Values of Structural Damage

Seismic Design Level	Building Type (Low-Rise)	Drift Ratio at the Threshold of Structural Damage			
		Slight	Moderate	Extensive	Complete
High-Code	W1/W2 C1L, S2L RM1L/RM2L, PC1/PC2L	0.004 0.005 0.004	0.012 0.010 0.008	0.040 0.030 0.024	0.100 0.080 0.070
Moderate-Code	W1/W2 C1L, S2L RM1L/RM2L, PC1/PC2L	0.004 0.005 0.004	0.010 0.009 0.007	0.031 0.023 0.019	0.075 0.060 0.053
Low-Code	W1/W2 C1L, S2L RM1L/RM2L,PC1/PC2L URML, C3L, S5L	0.004 0.005 0.004 0.003	0.010 0.008 0.006 0.006	0.031 0.020 0.016 0.015	0.075 0.050 0.044 0.035
Pre-Code	W1/W2 C1L, S2L RM1L/RM2L,PC1/PC2L URML, C3L, S5L	0.003 0.004 0.003 0.002	0.008 0.006 0.005 0.005	0.025 0.016 0.013 0.012	0.060 0.040 0.035 0.028

In general, values of the drift ratio that define Complete damage to Moderate-Code buildings are assumed to be 75% of the drift ratio that define Complete damage to High-Code buildings, and values of the drift ratio that define Complete damage to Low-Code buildings are assumed to be 63% of the drift ratios that define Complete damage to High-Code buildings. These assumptions are based on the recognition that post-yield capacity is significantly less in buildings designed with limited ductile detailing. Values of the drift ratio that define Slight damage were assumed to be the same for High-Code, Moderate-Code and Low-Code buildings, since this damage state typically does not exceed the building's elastic capacity.

Values of drift ratios that define Moderate and Extensive damage to Moderate-Code and Low-Code buildings are selected such that their distribution between Slight and Complete damage-state drift ratios is in proportion to the distribution of damage-state drift ratios for High-Code buildings.

Values of Pre-Code building drift ratios are based on the drift ratios for Low-Code buildings, reduced slightly to account for inferior performance anticipated for these older buildings. For each damage state, the drift ratio of a Pre-Code building is assumed to be 80% of the drift ratio of the Low-Code building of the same building type.

Drift ratios are reduced for taller buildings assuming that the deflected shape will not affect uniform distribution of drift over the building's height. For all damage states, drift ratios for mid-rise buildings are assumed to be 67% of those of low-rise buildings of the same type, and drift ratios for high-rise buildings are assumed to be 50% of those of low-rise buildings of the same type. Since mid-rise and high-rise buildings are much taller than low-rise buildings, median values of spectral displacement (i.e., drift ratio times height of building at the point of push-over mode displacement) are still much greater for mid-rise and high-rise buildings than for low-rise buildings.

The total variability of each structural damage state, β_{Sds}, is modeled by the combination of following three contributors to damage variability:

- uncertainty in the damage-state threshold of the structural system ($\beta_{M(Sds)}$ = 0.4, for all structural damage states and building types)
- variability in capacity (response) properties of the model building type/seismic design level of interest ($\beta_{C(Au)}$ = 0.25 for Code buildings, $\beta_{C(Au)}$ = 0.30 for Pre-Code buildings) and

- variability in response due to the spatial variability of ground motion

Each of these three contributors to damage state variability is assumed to be lognormally distributed random variables. Capacity and demand are dependent parameters and a convolution process is used to derive combined capacity/demand variability of each structural damage state. Capacity/demand variability is then combined with damage state uncertainty, as described in Section 5.4.3.3.

Tables 5.9a, 5.9b, 5.9c and 5.9d summarize median and lognormal standard deviation (β_{Sds}) values for Slight, Moderate, Extensive and Complete structural damage states High-Code, Moderate-Code, Low-Code and Pre-Code buildings, respectively. Note that for the following tables, shaded boxes indicate types that are not permitted by current seismic codes.

Table 5.9a Structural Fragility Curve Parameters - High-Code Seismic Design Level

Building Properties			Interstory Drift at Threshold of Damage State				Spectral Displacement (inches)							
Type	Height (inches)						Slight		Moderate		Extensive		Complete	
	Roof	Modal	Slight	Moderate	Extensive	Complete	Median	Beta	Median	Beta	Median	Beta	Median	Beta
W1	168	126	0.0040	0.0120	0.0400	0.1000	0.50	0.80	1.51	0.81	5.04	0.85	12.60	0.97
W2	288	216	0.0040	0.0120	0.0400	0.1000	0.86	0.81	2.59	0.88	8.64	0.90	21.60	0.83
S1L	288	216	0.0060	0.0120	0.0300	0.0800	1.30	0.80	2.59	0.76	6.48	0.69	17.28	0.72
S1M	720	540	0.0040	0.0080	0.0200	0.0533	2.16	0.65	4.32	0.66	10.80	0.67	28.80	0.74
S1H	1872	1123	0.0030	0.0060	0.0150	0.0400	3.37	0.64	6.74	0.64	16.85	0.65	44.93	0.67
S2L	288	216	0.0050	0.0100	0.0300	0.0800	1.08	0.81	2.16	0.89	6.48	0.94	17.28	0.83
S2M	720	540	0.0033	0.0067	0.0200	0.0533	1.80	0.67	3.60	0.67	10.80	0.68	28.80	0.79
S2H	1872	1123	0.0025	0.0050	0.0150	0.0400	2.81	0.63	5.62	0.63	16.85	0.64	44.93	0.71
S3	180	135	0.0040	0.0080	0.0240	0.0700	0.54	0.81	1.08	0.82	3.24	0.91	9.45	0.90
S4L	288	216	0.0040	0.0080	0.0240	0.0700	0.86	0.89	1.73	0.89	5.18	0.98	15.12	0.87
S4M	720	540	0.0027	0.0053	0.0160	0.0467	1.44	0.77	2.88	0.72	8.64	0.70	25.20	0.89
S4H	1872	1123	0.0020	0.0040	0.0120	0.0350	2.25	0.64	4.49	0.66	13.48	0.69	39.31	0.77
S5L														
S5M														
S5H														
C1L	240	180	0.0050	0.0100	0.0300	0.0800	0.90	0.81	1.80	0.84	5.40	0.86	14.40	0.81
C1M	600	450	0.0033	0.0067	0.0200	0.0533	1.50	0.68	3.00	0.67	9.00	0.68	24.00	0.81
C1H	1440	864	0.0025	0.0050	0.0150	0.0400	2.16	0.66	4.32	0.64	12.96	0.67	34.56	0.78
C2L	240	180	0.0040	0.0100	0.0300	0.0800	0.72	0.81	1.80	0.84	5.40	0.93	14.40	0.92
C2M	600	450	0.0027	0.0067	0.0200	0.0533	1.20	0.74	3.00	0.77	9.00	0.68	24.00	0.77
C2H	1440	864	0.0020	0.0050	0.0150	0.0400	1.73	0.68	4.32	0.65	12.96	0.66	34.56	0.75
C3L														
C3M														
C3H														
PC1	180	135	0.0040	0.0080	0.0240	0.0700	0.54	0.76	1.08	0.86	3.24	0.88	9.45	0.99
PC2L	240	180	0.0040	0.0080	0.0240	0.0700	0.72	0.84	1.44	0.88	4.32	0.98	12.60	0.94
PC2M	600	450	0.0027	0.0053	0.0160	0.0467	1.20	0.77	2.40	0.81	7.20	0.70	21.00	0.82
PC2H	1440	864	0.0020	0.0040	0.0120	0.0350	1.73	0.64	3.46	0.66	10.37	0.68	30.24	0.81
RM1L	240	180	0.0040	0.0080	0.0240	0.0700	0.72	0.84	1.44	0.86	4.32	0.92	12.60	1.01
RM1M	600	450	0.0027	0.0053	0.0160	0.0467	1.20	0.71	2.40	0.81	7.20	0.76	21.00	0.75
RM2L	240	180	0.0040	0.0080	0.0240	0.0700	0.72	0.80	1.44	0.81	4.32	0.91	12.60	0.98
RM2M	600	450	0.0027	0.0053	0.0160	0.0467	1.20	0.71	2.40	0.79	7.20	0.70	21.00	0.73
RM2H	1440	864	0.0020	0.0040	0.0120	0.0350	1.73	0.66	3.46	0.65	10.37	0.66	30.24	0.72
URML														
URMM														
MH	120	120	0.0040	0.0080	0.0240	0.0700	0.48	0.91	0.96	1.00	2.88	1.03	8.40	0.92

Table 5.9b Structural Fragility Curve Parameters – Moderate Code Seismic

Building Properties			Interstory Drift at Threshold of Damage State				Spectral Displacement (inches)							
Type	Height (inches)						Slight		Moderate		Extensive		Complete	
	Roof	Modal	Slight	Moderate	Extensive	Complete	Median	Beta	Median	Beta	Median	Beta	Median	Beta
W1	168	126	0.0040	0.0099	0.0306	0.0750	0.50	0.84	1.25	0.86	3.86	0.89	9.45	1.04
W2	288	216	0.0040	0.0099	0.0306	0.0750	0.86	0.89	2.14	0.95	6.62	0.95	16.20	0.92
S1L	288	216	0.0060	0.0104	0.0235	0.0600	1.30	0.80	2.24	0.75	5.08	0.74	12.96	0.88
S1M	720	540	0.0040	0.0069	0.0157	0.0400	2.16	0.65	3.74	0.68	8.46	0.69	21.60	0.87
S1H	1872	1123	0.0030	0.0052	0.0118	0.0300	3.37	0.64	5.83	0.64	13.21	0.71	33.70	0.83
S2L	288	216	0.0050	0.0087	0.0233	0.0600	1.08	0.93	1.87	0.92	5.04	0.93	12.96	0.93
S2M	720	540	0.0033	0.0058	0.0156	0.0400	1.80	0.70	3.12	0.69	8.40	0.69	21.60	0.89
S2H	1872	1123	0.0025	0.0043	0.0117	0.0300	2.81	0.66	4.87	0.64	13.10	0.69	33.70	0.80
S3	180	135	0.0040	0.0070	0.0187	0.0525	0.54	0.88	0.94	0.92	2.52	0.97	7.09	0.89
S4L	288	216	0.0040	0.0069	0.0187	0.0525	0.86	0.96	1.50	1.00	4.04	1.03	11.34	0.92
S4M	720	540	0.0027	0.0046	0.0125	0.0350	1.44	0.75	2.50	0.72	6.73	0.72	18.90	0.94
S4H	1872	1123	0.0020	0.0035	0.0093	0.0262	2.25	0.66	3.90	0.67	10.50	0.70	29.48	0.90
S5L														
S5M														
S5H														
C1L	240	180	0.0050	0.0087	0.0233	0.0600	0.90	0.89	1.56	0.90	4.20	0.90	10.80	0.89
C1M	600	450	0.0033	0.0058	0.0156	0.0400	1.50	0.70	2.60	0.70	7.00	0.70	18.00	0.89
C1H	1440	864	0.0025	0.0043	0.0117	0.0300	2.16	0.66	3.74	0.66	10.08	0.76	25.92	0.91
C2L	240	180	0.0040	0.0084	0.0232	0.0600	0.72	0.91	1.52	0.97	4.17	1.03	10.80	0.87
C2M	600	450	0.0027	0.0056	0.0154	0.0400	1.20	0.81	2.53	0.77	6.95	0.73	18.00	0.91
C2H	1440	864	0.0020	0.0042	0.0116	0.0300	1.73	0.66	3.64	0.68	10.00	0.70	25.92	0.87
C3L														
C3M														
C3H														
PC1	180	135	0.0040	0.0070	0.0187	0.0525	0.54	0.89	0.94	0.92	2.52	0.97	7.09	1.04
PC2L	240	180	0.0040	0.0069	0.0187	0.0525	0.72	0.96	1.25	1.00	3.37	1.03	9.45	0.88
PC2M	600	450	0.0027	0.0046	0.0125	0.0350	1.20	0.82	2.08	0.79	5.61	0.75	15.75	0.93
PC2H	1440	864	0.0020	0.0035	0.0094	0.0263	1.73	0.68	3.00	0.69	8.08	0.77	22.68	0.89
RM1L	240	180	0.0040	0.0069	0.0187	0.0525	0.72	0.96	1.25	0.99	3.37	1.05	9.45	0.94
RM1M	600	450	0.0027	0.0046	0.0125	0.0350	1.20	0.81	2.08	0.82	5.61	0.80	15.75	0.89
RM2L	240	180	0.0040	0.0069	0.0187	0.0525	0.72	0.91	1.25	0.96	3.37	1.02	9.45	0.93
RM2M	600	450	0.0027	0.0046	0.0125	0.0350	1.20	0.81	2.08	0.80	5.61	0.75	15.75	0.88
RM2H	1440	864	0.0020	0.0035	0.0094	0.0263	1.73	0.67	3.00	0.69	8.08	0.70	22.68	0.86
URML														
URMM														
MH	120	120	0.0040	0.0080	0.0240	0.0700	0.48	0.91	0.96	1.00	2.88	1.03	8.40	0.92

Design Level

Building Properties			Interstory Drift at Threshold of Damage State				Spectral Displacement (inches)							
Type	Height (inches)						Slight		Moderate		Extensive		Complete	
	Roof	Modal	Slight	Moderate	Extensive	Complete	Median	Beta	Median	Beta	Median	Beta	Median	Beta
W1	168	126	0.0040	0.0099	0.0306	0.0750	0.50	0.93	1.25	0.98	3.86	1.02	9.45	0.99
W2	288	216	0.0040	0.0099	0.0306	0.0750	0.86	0.97	2.14	0.90	6.62	0.89	16.20	0.99
S1L	288	216	0.0060	0.0096	0.0203	0.0500	1.30	0.77	2.07	0.78	4.38	0.78	10.80	0.96
S1M	720	540	0.0040	0.0064	0.0135	0.0333	2.16	0.68	3.44	0.78	7.30	0.85	18.00	0.98
S1H	1872	1123	0.0030	0.0048	0.0101	0.0250	3.37	0.66	5.37	0.70	11.38	0.76	28.08	0.92
S2L	288	216	0.0050	0.0080	0.0200	0.0500	1.08	0.96	1.73	0.89	4.32	0.86	10.80	0.98
S2M	720	540	0.0033	0.0053	0.0133	0.0333	1.80	0.70	2.88	0.73	7.20	0.85	18.00	0.98
S2H	1872	1123	0.0025	0.0040	0.0100	0.0250	2.81	0.66	4.49	0.67	11.23	0.74	28.08	0.92
S3	180	135	0.0040	0.0064	0.0161	0.0438	0.54	0.98	0.87	0.99	2.17	1.01	5.91	0.90
S4L	288	216	0.0040	0.0064	0.0161	0.0438	0.86	1.05	1.38	0.98	3.47	0.89	9.45	0.98
S4M	720	540	0.0027	0.0043	0.0107	0.0292	1.44	0.76	2.31	0.78	5.78	0.90	15.75	0.99
S4H	1872	1123	0.0020	0.0032	0.0080	0.0219	2.25	0.70	3.60	0.75	9.01	0.90	24.57	0.98
S5L	288	216	0.0030	0.0060	0.0150	0.0350	0.65	1.11	1.30	1.04	3.24	0.99	7.56	0.95
S5M	720	540	0.0020	0.0040	0.0100	0.0233	1.08	0.77	2.16	0.79	5.40	0.87	12.60	0.98
S5H	1872	1123	0.0015	0.0030	0.0075	0.0175	1.68	0.70	3.37	0.73	8.42	0.89	19.66	0.97
C1L	240	180	0.0050	0.0080	0.0200	0.0500	0.90	0.95	1.44	0.91	3.60	0.85	9.00	0.97
C1M	600	450	0.0033	0.0053	0.0133	0.0333	1.50	0.70	2.40	0.74	6.00	0.86	15.00	0.98
C1H	1440	864	0.0025	0.0040	0.0100	0.0250	2.16	0.70	3.46	0.81	8.64	0.89	21.60	0.98
C2L	240	180	0.0040	0.0076	0.0197	0.0500	0.72	1.04	1.37	1.02	3.55	0.99	9.00	0.95
C2M	600	450	0.0027	0.0051	0.0132	0.0333	1.20	0.82	2.29	0.81	5.92	0.81	15.00	0.99
C2H	1440	864	0.0020	0.0038	0.0099	0.0250	1.73	0.68	3.30	0.73	8.53	0.84	21.60	0.95
C3L	240	180	0.0030	0.0060	0.0150	0.0350	0.54	1.09	1.08	1.07	2.70	1.08	6.30	0.91
C3M	600	450	0.0020	0.0040	0.0100	0.0233	0.90	0.85	1.80	0.83	4.50	0.79	10.50	0.98
C3H	1440	864	0.0015	0.0030	0.0075	0.0175	1.30	0.71	2.59	0.74	6.48	0.90	15.12	0.97
PC1	180	135	0.0040	0.0064	0.0161	0.0438	0.54	1.00	0.87	1.05	2.17	1.12	5.91	0.89
PC2L	240	180	0.0040	0.0064	0.0161	0.0438	0.72	1.08	1.15	1.03	2.89	0.98	7.88	0.96
PC2M	600	450	0.0027	0.0043	0.0107	0.0292	1.20	0.81	1.92	0.79	4.81	0.84	13.12	0.99
PC2H	1440	864	0.0020	0.0032	0.0080	0.0219	1.73	0.71	2.77	0.75	6.93	0.89	18.90	0.98
RM1L	240	180	0.0040	0.0064	0.0161	0.0438	0.72	1.11	1.15	1.10	2.89	1.10	7.88	0.92
RM1M	600	450	0.0027	0.0043	0.0107	0.0292	1.20	0.87	1.92	0.84	4.81	0.79	13.12	0.96
RM2L	240	180	0.0040	0.0064	0.0161	0.0438	0.72	1.05	1.15	1.07	2.89	1.09	7.88	0.91
RM2M	600	450	0.0027	0.0043	0.0107	0.0292	1.20	0.84	1.92	0.81	4.81	0.77	13.12	0.96
RM2H	1440	864	0.0020	0.0032	0.0080	0.0219	1.73	0.69	2.77	0.72	6.93	0.87	18.90	0.96
URML	180	135	0.0030	0.0060	0.0150	0.0350	0.41	0.99	0.81	1.05	2.03	1.10	4.73	1.08
URMM	420	315	0.0020	0.0040	0.0100	0.0233	0.63	0.91	1.26	0.92	3.15	0.87	7.35	0.91
MH	120	120	0.0040	0.0080	0.0240	0.0700	0.48	0.91	0.96	1.00	2.88	1.03	8.40	0.92

Table 5.9c Structural Fragility Curve Parameters - Low-Code Seismic Design Level

Table 5.9d Structural Fragility Curve Parameters - Pre-Code Seismic Design Level

Building Properties			Interstory Drift at Threshold of Damage State				Spectral Displacement (inches)							
Type	Height (inches)						Slight		Moderate		Extensive		Complete	
	Roof	Modal	Slight	Moderate	Extensive	Complete	Median	Beta	Median	Beta	Median	Beta	Median	Beta
W1	168	126	0.0032	0.0079	0.0245	0.0600	0.40	1.01	1.00	1.05	3.09	1.07	7.56	1.06
W2	288	216	0.0032	0.0079	0.0245	0.0600	0.69	1.04	1.71	0.97	5.29	0.90	12.96	0.99
S1L	288	216	0.0048	0.0076	0.0162	0.0400	1.04	0.85	1.65	0.82	3.50	0.80	8.64	0.95
S1M	720	540	0.0032	0.0051	0.0108	0.0267	1.73	0.70	2.76	0.75	5.84	0.81	14.40	0.98
S1H	1872	1123	0.0024	0.0038	0.0081	0.0200	2.70	0.69	4.30	0.71	9.11	0.85	22.46	0.93
S2L	288	216	0.0040	0.0064	0.0160	0.0400	0.86	1.01	1.38	0.96	3.46	0.88	8.64	0.98
S2M	720	540	0.0027	0.0043	0.0107	0.0267	1.44	0.73	2.30	0.75	5.76	0.80	14.40	0.98
S2H	1872	1123	0.0020	0.0032	0.0080	0.0200	2.25	0.70	3.59	0.70	8.99	0.84	22.46	0.91
S3	180	135	0.0032	0.0051	0.0128	0.0350	0.43	1.06	0.69	1.03	1.73	1.07	4.73	0.89
S4L	288	216	0.0032	0.0051	0.0128	0.0350	0.69	1.11	1.11	1.03	2.77	0.99	7.56	0.98
S4M	720	540	0.0021	0.0034	0.0086	0.0233	1.15	0.81	1.85	0.80	4.62	0.94	12.60	1.00
S4H	1872	1123	0.0016	0.0026	0.0064	0.0175	1.80	0.73	2.88	0.75	7.21	0.90	19.66	0.97
S5L	288	216	0.0024	0.0048	0.0120	0.0280	0.52	1.20	1.04	1.11	2.59	1.08	6.05	0.95
S5M	720	540	0.0016	0.0032	0.0080	0.0187	0.86	0.85	1.73	0.83	4.32	0.94	10.08	0.99
S5H	1872	1123	0.0012	0.0024	0.0060	0.0140	1.35	0.72	2.70	0.75	6.74	0.92	15.72	0.96
C1L	240	180	0.0040	0.0064	0.0160	0.0400	0.72	0.98	1.15	0.94	2.88	0.90	7.20	0.97
C1M	600	450	0.0027	0.0043	0.0107	0.0267	1.20	0.73	1.92	0.77	4.80	0.83	12.00	0.98
C1H	1440	864	0.0020	0.0032	0.0080	0.0200	1.73	0.71	2.76	0.80	6.91	0.94	17.28	1.01
C2L	240	180	0.0032	0.0061	0.0158	0.0400	0.58	1.11	1.10	1.09	2.84	1.07	7.20	0.93
C2M	600	450	0.0021	0.0041	0.0105	0.0267	0.96	0.86	1.83	0.83	4.74	0.80	12.00	0.98
C2H	1440	864	0.0016	0.0031	0.0079	0.0200	1.38	0.73	2.64	0.75	6.82	0.92	17.28	0.97
C3L	240	180	0.0024	0.0048	0.0120	0.0280	0.43	1.19	0.86	1.15	2.16	1.15	5.04	0.92
C3M	600	450	0.0016	0.0032	0.0080	0.0187	0.72	0.90	1.44	0.86	3.60	0.90	8.40	0.96
C3H	1440	864	0.0012	0.0024	0.0060	0.0140	1.04	0.73	2.07	0.75	5.18	0.90	12.10	0.95
PC1	180	135	0.0032	0.0051	0.0128	0.0350	0.43	1.14	0.69	1.14	1.73	1.17	4.73	0.98
PC2L	240	180	0.0032	0.0051	0.0128	0.0350	0.58	1.14	0.92	1.10	2.31	1.10	6.30	0.93
PC2M	600	450	0.0021	0.0034	0.0086	0.0233	0.96	0.87	1.54	0.83	3.85	0.91	10.50	1.00
PC2H	1440	864	0.0016	0.0026	0.0064	0.0175	1.38	0.74	2.21	0.75	5.55	0.91	15.12	0.96
RM1L	240	180	0.0032	0.0051	0.0128	0.0350	0.58	1.20	0.92	1.17	2.31	1.17	6.30	0.94
RM1M	600	450	0.0021	0.0034	0.0086	0.0233	0.96	0.91	1.54	0.89	3.85	0.89	10.50	0.96
RM2L	240	180	0.0032	0.0051	0.0128	0.0350	0.58	1.14	0.92	1.10	2.31	1.15	6.30	0.92
RM2M	600	450	0.0021	0.0034	0.0086	0.0233	0.96	0.89	1.54	0.87	3.85	0.87	10.50	0.96
RM2H	1440	864	0.0016	0.0026	0.0064	0.0175	1.38	0.75	2.21	0.75	5.55	0.84	15.12	0.94
URML	180	135	0.0024	0.0048	0.0120	0.0280	0.32	1.15	0.65	1.19	1.62	1.20	3.78	1.18
URMM	420	315	0.0016	0.0032	0.0080	0.0187	0.50	0.99	1.01	0.97	2.52	0.90	5.88	0.88
MH	120	120	0.0032	0.0064	0.0192	0.0560	0.38	1.11	0.77	1.10	2.30	0.95	6.72	0.97

5.4.3.5 Nonstructural Damage - Drift-Sensitive Components

Table 5.10 summarizes drift ratios used by the Methodology to define the median values of damage fragility curves for drift-sensitive nonstructural components of buildings. Nonstructural damage drift ratios are assumed to be the same for each building type and each seismic design level.

Table 5.10 Drift Ratios Used to Define Median Values of Damage for Nonstructural Drift-Sensitive Components

Drift Ratio at the Threshold of Nonstructural Damage			
Slight	Moderate	Extensive	Complete
0.004	0.008	0.025	0.050

Median values of drift-sensitive nonstructural fragility curves are based on global building displacement (in inches), calculated as the product of: (1) drift ratio, (2) building height and (3) the fraction of building height at the location of push-over mode displacement (α_2).

The total variability of each nonstructural drift-sensitive damage state, β_{NSDds}, is modeled by the combination of following three contributors to damage variability:

- uncertainty in the damage-state threshold of nonstructural components ($\beta_{M(NSDds)}$ = 0.5, for all damage states and building types),
- variability in capacity (response) properties of the model building type that contains the nonstructural components of interest ($\beta_{C(Au)}$ = 0.25 for Code buildings, $\beta_{C(Au)}$ = 0.30 for Pre-Code buildings), and
- variability in response of the model building type due to the spatial variability of ground motion demand ($\beta_{D(A)}$ = 0.45 and $\beta_{C(V)}$ = 0.50).

Each of these three contributors to damage state variability is assumed to be lognormally distributed random variables. Capacity and demand are dependent parameters and a convolution process is used to derive combined capacity/demand variability of each nonstructural damage state. Capacity/demand variability is then combined with damage state uncertainty, as described in Section 5.4.3.3.

Table 5.11a, 5.11b, 5.11c and 5.11d summarize median and lognormal standard deviation (β_{NSDds}) values for Slight, Moderate, Extensive and Complete nonstructural drift-sensitive damage states for High-Code, Moderate-Code, Low-Code and Pre-Code buildings, respectively. Median values are the same for all design levels. Lognormal standard deviation values are slightly different for each seismic design level. Note that for the following tables, shaded boxes indicate types that are not permitted by current seismic codes.

Table 5.11 Nonstructural Drift-Sensitive Fragility Curve Parameters - High-Code Seismic Design Level

Building Type	Median Spectral Displacement (inches) and Logstandard Deviation (Beta)							
	Slight		Moderate		Extensive		Complete	
	Median	Beta	Median	Beta	Median	Beta	Median	Beta
W1	0.50	0.85	1.01	0.88	3.15	0.88	6.30	0.94
W2	0.86	0.87	1.73	0.89	5.40	0.96	10.80	0.94
S1L	0.86	0.81	1.73	0.85	5.40	0.77	10.80	0.77
S1M	2.16	0.71	4.32	0.72	13.50	0.72	27.00	0.80
S1H	4.49	0.72	8.99	0.71	28.08	0.74	56.16	0.77
S2L	0.86	0.84	1.73	0.90	5.40	0.97	10.80	0.92
S2M	2.16	0.71	4.32	0.74	13.50	0.74	27.00	0.84
S2H	4.49	0.71	8.99	0.71	28.08	0.72	56.16	0.78
S3	0.54	0.86	1.08	0.88	3.38	0.98	6.75	0.98
S4L	0.86	0.93	1.73	0.94	5.40	1.01	10.80	0.99
S4M	2.16	0.80	4.32	0.76	13.50	0.76	27.00	0.93
S4H	4.49	0.72	8.99	0.72	28.08	0.79	56.16	0.91
S5L								
S5M								
S5H								
C1L	0.72	0.84	1.44	0.88	4.50	0.90	9.00	0.88
C1M	1.80	0.72	3.60	0.73	11.25	0.74	22.50	0.84
C1H	3.46	0.71	6.91	0.71	21.60	0.78	43.20	0.88
C2L	0.72	0.87	1.44	0.88	4.50	0.97	9.00	0.99
C2M	1.80	0.84	3.60	0.82	11.25	0.74	22.50	0.81
C2H	3.46	0.71	6.91	0.72	21.60	0.74	43.20	0.85
C3L								
C3M								
C3H								
PC1	0.54	0.82	1.08	0.91	3.38	0.95	6.75	1.03
PC2L	0.72	0.89	1.44	0.93	4.50	1.03	9.00	1.04
PC2M	1.80	0.87	3.60	0.83	11.25	0.77	22.50	0.89
PC2H	3.46	0.73	6.91	0.73	21.60	0.77	43.20	0.89
RM1L	0.72	0.89	1.44	0.91	4.50	0.97	9.00	1.06
RM1M	1.80	0.81	3.60	0.86	11.25	0.80	22.50	0.81
RM2L	0.72	0.85	1.44	0.87	4.50	0.95	9.00	1.03
RM2M	1.80	0.82	3.60	0.84	11.25	0.76	22.50	0.80
RM2H	3.46	0.71	6.91	0.73	21.60	0.73	43.20	0.85
URML								
URMM								
MH	0.48	0.96	0.96	1.05	3.00	1.07	6.00	0.93

Table 5.11b Nonstructural Drift-Sensitive Fragility Curve Parameters - Moderate-Code Seismic Design Level

Building Type	Median Spectral Displacement (inches) and Logstandard Deviation (Beta)							
	Slight		Moderate		Extensive		Complete	
	Median	Beta	Median	Beta	Median	Beta	Median	Beta
W1	0.50	0.89	1.01	0.91	3.15	0.90	6.30	1.04
W2	0.86	0.94	1.73	0.99	5.40	1.00	10.80	0.90
S1L	0.86	0.84	1.73	0.83	5.40	0.79	10.80	0.87
S1M	2.16	0.71	4.32	0.74	13.50	0.85	27.00	0.95
S1H	4.49	0.71	8.99	0.74	28.08	0.84	56.16	0.95
S2L	0.86	0.93	1.73	0.99	5.40	0.96	10.80	0.92
S2M	2.16	0.74	4.32	0.74	13.50	0.85	27.00	0.96
S2H	4.49	0.72	8.99	0.73	28.08	0.80	56.16	0.94
S3	0.54	0.93	1.08	0.98	3.38	1.01	6.75	0.94
S4L	0.86	1.00	1.73	1.06	5.40	0.99	10.80	0.96
S4M	2.16	0.77	4.32	0.80	13.50	0.95	27.00	1.04
S4H	4.49	0.73	8.99	0.82	28.08	0.93	56.16	1.01
S5L								
S5M								
S5H								
C1L	0.72	0.93	1.44	0.96	4.50	0.94	9.00	0.88
C1M	1.80	0.77	3.60	0.76	11.25	0.87	22.50	0.98
C1H	3.46	0.74	6.91	0.80	21.60	0.94	43.20	1.03
C2L	0.72	0.96	1.44	1.00	4.50	1.06	9.00	0.95
C2M	1.80	0.84	3.60	0.81	11.25	0.83	22.50	0.98
C2H	3.46	0.73	6.91	0.76	21.60	0.89	43.20	0.99
C3L								
C3M								
C3H								
PC1	0.54	0.94	1.08	0.99	3.38	1.05	6.75	1.08
PC2L	0.72	1.00	1.44	1.06	4.50	1.07	9.00	0.93
PC2M	1.80	0.85	3.60	0.83	11.25	0.92	22.50	1.00
PC2H	3.46	0.74	6.91	0.79	21.60	0.93	43.20	1.02
RM1L	0.72	1.00	1.44	1.06	4.50	1.12	9.00	1.01
RM1M	1.80	0.88	3.60	0.85	11.25	0.84	22.50	0.98
RM2L	0.72	0.96	1.44	1.02	4.50	1.10	9.00	0.99
RM2M	1.80	0.88	3.60	0.83	11.25	0.81	22.50	0.98
RM2H	3.46	0.73	6.91	0.76	21.60	0.88	43.20	0.99
URML								
URMM								
MH	0.48	0.96	0.96	1.05	3.00	1.07	6.00	0.93

Table 5.11c Nonstructural Drift-Sensitive Fragility Curve Parameters - Low-Code Seismic Design Level

Building Type	Median Spectral Displacement (inches) and Logstandard Deviation (Beta)							
	Slight		Moderate		Extensive		Complete	
	Median	Beta	Median	Beta	Median	Beta	Median	Beta
W1	0.50	0.98	1.01	0.99	3.15	1.02	6.30	1.09
W2	0.86	1.01	1.73	0.97	5.40	0.93	10.80	1.03
S1L	0.86	0.86	1.73	0.84	5.40	0.88	10.80	1.00
S1M	2.16	0.74	4.32	0.89	13.50	0.99	27.00	1.05
S1H	4.49	0.75	8.99	0.87	28.08	0.97	56.16	1.04
S2L	0.86	1.01	1.73	0.94	5.40	0.94	10.80	1.03
S2M	2.16	0.77	4.32	0.87	13.50	0.99	27.00	1.05
S2H	4.49	0.74	8.99	0.86	28.08	0.97	56.16	1.05
S3	0.54	1.03	1.08	1.02	3.38	0.96	6.75	0.99
S4L	0.86	1.09	1.73	0.99	5.40	0.96	10.80	1.03
S4M	2.16	0.83	4.32	0.95	13.50	1.04	27.00	1.07
S4H	4.49	0.84	8.99	0.95	28.08	1.05	56.16	1.07
S5L	0.86	1.14	1.73	1.04	5.40	0.98	10.80	1.01
S5M	2.16	0.84	4.32	0.95	13.50	1.03	27.00	1.07
S5H	4.49	0.84	8.99	0.95	28.08	1.03	56.16	1.06
C1L	0.72	0.99	1.44	0.96	4.50	0.90	9.00	1.01
C1M	1.80	0.79	3.60	0.88	11.25	0.99	22.50	1.06
C1H	3.46	0.87	6.91	0.96	21.60	1.02	43.20	1.06
C2L	0.72	1.08	1.44	1.05	4.50	0.95	9.00	0.99
C2M	1.80	0.84	3.60	0.87	11.25	1.00	22.50	1.06
C2H	3.46	0.79	6.91	0.93	21.60	0.99	43.20	1.07
C3L	0.72	1.13	1.44	1.08	4.50	0.95	9.00	1.00
C3M	1.80	0.88	3.60	0.92	11.25	1.00	22.50	1.06
C3H	3.46	0.83	6.91	0.96	21.60	1.02	43.20	1.06
PC1	0.54	1.05	1.08	1.10	3.38	1.10	6.75	0.93
PC2L	0.72	1.12	1.44	1.04	4.50	0.93	9.00	1.02
PC2M	1.80	0.86	3.60	0.93	11.25	1.02	22.50	1.07
PC2H	3.46	0.83	6.91	0.94	21.60	1.04	43.20	1.07
RM1L	0.72	1.15	1.44	1.12	4.50	1.03	9.00	0.99
RM1M	1.80	0.89	3.60	0.89	11.25	1.00	22.50	1.05
RM2L	0.72	1.09	1.44	1.08	4.50	1.01	9.00	0.99
RM2M	1.80	0.85	3.60	0.86	11.25	0.99	22.50	1.06
RM2H	3.46	0.79	6.91	0.92	21.60	0.99	43.20	1.06
URML	0.54	1.07	1.08	1.13	3.38	1.16	6.75	1.01
URMM	1.26	0.97	2.52	0.91	7.88	0.98	15.75	1.04
MH	0.48	0.96	0.96	1.05	3.00	1.07	6.00	0.93

Table 5.11d Nonstructural Drift-Sensitive Fragility Curve Parameters - Pre-Code Seismic Design Level

Building Type	Median Spectral Displacement (inches) and Logstandard Deviation (Beta)							
	Slight		Moderate		Extensive		Complete	
	Median	Beta	Median	Beta	Median	Beta	Median	Beta
W1	0.50	1.07	1.01	1.11	3.15	1.11	6.30	1.14
W2	0.86	1.06	1.73	1.00	5.40	0.93	10.80	1.01
S1L	0.86	0.90	1.73	0.87	5.40	0.91	10.80	1.02
S1M	2.16	0.80	4.32	0.92	13.50	0.99	27.00	1.06
S1H	4.49	0.79	8.99	0.89	28.08	1.00	56.16	1.07
S2L	0.86	1.06	1.73	0.97	5.40	0.96	10.80	1.04
S2M	2.16	0.80	4.32	0.90	13.50	1.02	27.00	1.06
S2H	4.49	0.79	8.99	0.89	28.08	0.99	56.16	1.06
S3	0.54	1.11	1.08	1.05	3.38	0.96	6.75	1.00
S4L	0.86	1.12	1.73	1.00	5.40	0.99	10.80	1.05
S4M	2.16	0.86	4.32	0.99	13.50	1.06	27.00	1.10
S4H	4.49	0.88	8.99	0.99	28.08	1.07	56.16	1.09
S5L	0.86	1.18	1.73	1.06	5.40	0.98	10.80	1.03
S5M	2.16	0.86	4.32	0.99	13.50	1.05	27.00	1.09
S5H	4.49	0.88	8.99	0.91	28.08	1.05	56.16	1.09
C1L	0.72	1.02	1.44	0.98	4.50	0.93	9.00	1.03
C1M	1.80	0.81	3.60	0.91	11.25	1.02	22.50	1.06
C1H	3.46	0.90	6.91	0.99	21.60	1.05	43.20	1.10
C2L	0.72	1.14	1.44	1.08	4.50	0.97	9.00	1.00
C2M	1.80	0.88	3.60	0.90	11.25	1.03	22.50	1.07
C2H	3.46	0.83	6.91	0.97	21.60	1.05	43.20	1.07
C3L	0.72	1.19	1.44	1.11	4.50	0.99	9.00	1.02
C3M	1.80	0.92	3.60	0.95	11.25	1.03	22.50	1.09
C3H	3.46	0.86	6.91	0.90	21.60	1.04	43.20	1.09
PC1	0.54	1.18	1.08	1.16	3.38	1.12	6.75	0.95
PC2L	0.72	1.16	1.44	1.06	4.50	0.96	9.00	1.02
PC2M	1.80	0.87	3.60	0.95	11.25	1.04	22.50	1.07
PC2H	3.46	0.87	6.91	0.99	21.60	1.06	43.20	1.08
RM1L	0.72	1.22	1.44	1.14	4.50	1.03	9.00	0.99
RM1M	1.80	0.93	3.60	0.92	11.25	1.02	22.50	1.07
RM2L	0.72	1.17	1.44	1.12	4.50	1.01	9.00	0.99
RM2M	1.80	0.89	3.60	0.90	11.25	1.01	22.50	1.07
RM2H	3.46	0.82	6.91	0.96	21.60	1.04	43.20	1.07
URML	0.54	1.21	1.08	1.23	3.38	1.23	6.75	1.03
URMM	1.26	0.99	2.52	0.95	7.88	0.99	15.75	1.06
MH	0.48	1.15	0.96	1.09	3.00	0.93	6.00	0.99

5.4.3.6 Nonstructural Damage - Acceleration-Sensitive Components

Table 5.12 summarizes the peak floor acceleration values used by the Methodology to define the median values of fragility curves for acceleration-sensitive nonstructural components of buildings. Nonstructural damage acceleration values are assumed to be the same for each model building type, but to vary by seismic design level.

Table 5.12 Peak Floor Accelerations Used to Define Median Values of Damage to Nonstructural Acceleration-Sensitive Components

Seismic Design Level	Floor Acceleration at the Threshold of Nonstructural Damage (g)			
	Slight	Moderate	Extensive	Complete
High-Code	0.30	0.60	1.20	2.40
Moderate-Code	0.25	0.50	1.00	2.00
Low-Code	0.20	0.40	0.80	1.60
Pre-Code	0.20	0.40	0.80	1.60

The floor acceleration values are used directly as median values, assuming average upper-floor demand is represented by response at the point of the push-over mode displacement.

The total variability of each damage state, β_{NSAds}, is modeled by the combination of following three contributors to nonstructural acceleration-sensitive damage variability:

- uncertainty in the damage-state threshold of nonstructural components ($\beta_{M(NSAds)}$ = 0.6, for all damage states and building types),
- variability in capacity (response) properties of the model building type that contains the nonstructural components of interest ($\beta_{C(Au)}$ = 0.25 for Code buildings, $\beta_{C(Au)}$ = 0.30 for Pre-Code buildings), and
- variability in response of the model building type due to the spatial variability of ground motion demand ($\beta_{D(A)}$ = 0.45 and $\beta_{C(V)}$ = 0.50).

Each of these three contributors to damage state variability is assumed to be lognormally distributed random variables. Capacity and demand are dependent parameters and a convolution process is used to derive combined capacity/demand variability of each nonstructural damage state. Capacity/demand variability is then combined with damage state uncertainty, as described in Section 5.4.3.3.

Tables 5.13a, 5.13b, 5.13c and 5.13d summarize median and lognormal standard deviation (β_{NSAds}) values for Slight, Moderate, Extensive and Complete nonstructural acceleration-sensitive damage states for High-Code. Moderate-Code, Low-Code and Pre-Code buildings, respectively. Median values are the same for all building types. Lognormal standard deviation values are slightly different for each building type. Note that for the following tables, shaded boxes indicate types that are not permitted by current seismic codes.

Table 5.13a Nonstructural Acceleration-Sensitive Fragility Curve Parameters - High-Code Seismic Design Level

Building Type	Median Spectral Acceleration (g) and Logstandard Deviation (Beta)							
	Slight		Moderate		Extensive		Complete	
	Median	Beta	Median	Beta	Median	Beta	Median	Beta
W1	0.30	0.73	0.60	0.68	1.20	0.68	2.40	0.68
W2	0.30	0.70	0.60	0.67	1.20	0.67	2.40	0.68
S1L	0.30	0.67	0.60	0.67	1.20	0.68	2.40	0.67
S1M	0.30	0.67	0.60	0.68	1.20	0.67	2.40	0.67
S1H	0.30	0.68	0.60	0.67	1.20	0.67	2.40	0.67
S2L	0.30	0.67	0.60	0.67	1.20	0.67	2.40	0.67
S2M	0.30	0.69	0.60	0.66	1.20	0.66	2.40	0.66
S2H	0.30	0.68	0.60	0.66	1.20	0.65	2.40	0.65
S3	0.30	0.68	0.60	0.67	1.20	0.67	2.40	0.67
S4L	0.30	0.68	0.60	0.68	1.20	0.67	2.40	0.67
S4M	0.30	0.67	0.60	0.65	1.20	0.66	2.40	0.66
S4H	0.30	0.67	0.60	0.66	1.20	0.65	2.40	0.65
S5L								
S5M								
S5H								
C1L	0.30	0.68	0.60	0.68	1.20	0.67	2.40	0.67
C1M	0.30	0.68	0.60	0.68	1.20	0.66	2.40	0.66
C1H	0.30	0.66	0.60	0.66	1.20	0.66	2.40	0.66
C2L	0.30	0.69	0.60	0.67	1.20	0.66	2.40	0.64
C2M	0.30	0.70	0.60	0.65	1.20	0.65	2.40	0.65
C2H	0.30	0.68	0.60	0.66	1.20	0.65	2.40	0.65
C3L								
C3M								
C3H								
PC1	0.30	0.74	0.60	0.67	1.20	0.67	2.40	0.64
PC2L	0.30	0.68	0.60	0.67	1.20	0.67	2.40	0.67
PC2M	0.30	0.68	0.60	0.65	1.20	0.66	2.40	0.66
PC2H	0.30	0.67	0.60	0.65	1.20	0.65	2.40	0.65
RM1L	0.30	0.70	0.60	0.67	1.20	0.67	2.40	0.63
RM1M	0.30	0.72	0.60	0.66	1.20	0.65	2.40	0.65
RM2L	0.30	0.70	0.60	0.66	1.20	0.67	2.40	0.64
RM2M	0.30	0.72	0.60	0.65	1.20	0.65	2.40	0.65
RM2H	0.30	0.70	0.60	0.65	1.20	0.65	2.40	0.65
URML								
URMM								
MH	0.30	0.65	0.60	0.67	1.20	0.67	2.40	0.67

Table 5.13b Nonstructural Acceleration-Sensitive Fragility Curve Parameters - Moderate-Code Seismic Design Level

Building Type	Median Spectral Acceleration (g) and Logstandard Deviation (Beta)							
	Slight		Moderate		Extensive		Complete	
	Median	Beta	Median	Beta	Median	Beta	Median	Beta
W1	0.25	0.73	0.50	0.68	1.00	0.67	2.00	0.64
W2	0.25	0.68	0.50	0.67	1.00	0.68	2.00	0.68
S1L	0.25	0.67	0.50	0.66	1.00	0.67	2.00	0.67
S1M	0.25	0.66	0.50	0.67	1.00	0.67	2.00	0.67
S1H	0.25	0.66	0.50	0.68	1.00	0.68	2.00	0.68
S2L	0.25	0.66	0.50	0.66	1.00	0.68	2.00	0.68
S2M	0.25	0.66	0.50	0.65	1.00	0.65	2.00	0.65
S2H	0.25	0.65	0.50	0.65	1.00	0.65	2.00	0.65
S3	0.25	0.67	0.50	0.66	1.00	0.65	2.00	0.65
S4L	0.25	0.66	0.50	0.66	1.00	0.66	2.00	0.66
S4M	0.25	0.65	0.50	0.65	1.00	0.65	2.00	0.65
S4H	0.25	0.65	0.50	0.66	1.00	0.66	2.00	0.66
S5L								
S5M								
S5H								
C1L	0.25	0.67	0.50	0.66	1.00	0.66	2.00	0.66
C1M	0.25	0.66	0.50	0.65	1.00	0.63	2.00	0.63
C1H	0.25	0.65	0.50	0.67	1.00	0.67	2.00	0.67
C2L	0.25	0.68	0.50	0.66	1.00	0.68	2.00	0.68
C2M	0.25	0.67	0.50	0.64	1.00	0.67	2.00	0.67
C2H	0.25	0.66	0.50	0.65	1.00	0.65	2.00	0.65
C3L								
C3M								
C3H								
PC1	0.25	0.68	0.50	0.67	1.00	0.66	2.00	0.66
PC2L	0.25	0.66	0.50	0.66	1.00	0.65	2.00	0.65
PC2M	0.25	0.65	0.50	0.65	1.00	0.65	2.00	0.65
PC2H	0.25	0.64	0.50	0.65	1.00	0.65	2.00	0.65
RM1L	0.25	0.68	0.50	0.67	1.00	0.67	2.00	0.67
RM1M	0.25	0.67	0.50	0.64	1.00	0.67	2.00	0.67
RM2L	0.25	0.68	0.50	0.66	1.00	0.67	2.00	0.67
RM2M	0.25	0.67	0.50	0.64	1.00	0.67	2.00	0.67
RM2H	0.25	0.66	0.50	0.64	1.00	0.64	2.00	0.64
URML								
URMM								
MH	0.25	0.65	0.50	0.67	1.00	0.67	2.00	0.67

Table 5.13c Nonstructural Acceleration-Sensitive Fragility Curve Parameters - Low-Code Seismic Design Level

Building Type	Median Spectral Acceleration (g) and Logstandard Deviation (Beta)							
	Slight		Moderate		Extensive		Complete	
	Median	Beta	Median	Beta	Median	Beta	Median	Beta
W1	0.20	0.71	0.40	0.68	0.80	0.66	1.60	0.66
W2	0.20	0.67	0.40	0.67	0.80	0.70	1.60	0.70
S1L	0.20	0.65	0.40	0.68	0.80	0.68	1.60	0.68
S1M	0.20	0.66	0.40	0.68	0.80	0.68	1.60	0.68
S1H	0.20	0.67	0.40	0.65	0.80	0.65	1.60	0.65
S2L	0.20	0.65	0.40	0.68	0.80	0.68	1.60	0.68
S2M	0.20	0.65	0.40	0.68	0.80	0.68	1.60	0.68
S2H	0.20	0.65	0.40	0.68	0.80	0.68	1.60	0.68
S3	0.20	0.65	0.40	0.68	0.80	0.68	1.60	0.68
S4L	0.20	0.65	0.40	0.68	0.80	0.68	1.60	0.68
S4M	0.20	0.65	0.40	0.68	0.80	0.68	1.60	0.68
S4H	0.20	0.65	0.40	0.68	0.80	0.68	1.60	0.68
S5L	0.20	0.65	0.40	0.68	0.80	0.67	1.60	0.67
S5M	0.20	0.64	0.40	0.68	0.80	0.67	1.60	0.67
S5H	0.20	0.65	0.40	0.68	0.80	0.68	1.60	0.68
C1L	0.20	0.65	0.40	0.68	0.80	0.68	1.60	0.68
C1M	0.20	0.65	0.40	0.68	0.80	0.68	1.60	0.68
C1H	0.20	0.67	0.40	0.67	0.80	0.67	1.60	0.67
C2L	0.20	0.66	0.40	0.67	0.80	0.66	1.60	0.66
C2M	0.20	0.64	0.40	0.66	0.80	0.65	1.60	0.65
C2H	0.20	0.64	0.40	0.66	0.80	0.66	1.60	0.66
C3L	0.20	0.65	0.40	0.67	0.80	0.66	1.60	0.66
C3M	0.20	0.64	0.40	0.67	0.80	0.66	1.60	0.66
C3H	0.20	0.64	0.40	0.67	0.80	0.67	1.60	0.67
PC1	0.20	0.66	0.40	0.66	0.80	0.66	1.60	0.66
PC2L	0.20	0.65	0.40	0.68	0.80	0.68	1.60	0.68
PC2M	0.20	0.64	0.40	0.68	0.80	0.68	1.60	0.68
PC2H	0.20	0.64	0.40	0.67	0.80	0.67	1.60	0.67
RM1L	0.20	0.66	0.40	0.67	0.80	0.64	1.60	0.64
RM1M	0.20	0.64	0.40	0.66	0.80	0.64	1.60	0.64
RM2L	0.20	0.66	0.40	0.67	0.80	0.64	1.60	0.64
RM2M	0.20	0.64	0.40	0.66	0.80	0.65	1.60	0.65
RM2H	0.20	0.64	0.40	0.66	0.80	0.66	1.60	0.66
URML	0.20	0.68	0.40	0.65	0.80	0.65	1.60	0.65
URMM	0.20	0.64	0.40	0.66	0.80	0.66	1.60	0.66
MH	0.20	0.65	0.40	0.67	0.80	0.67	1.60	0.67

Table 5.13d Nonstructural Acceleration-Sensitive Fragility Curve Parameters - Pre-Code Seismic Design Level

Building Type	Median Spectral Acceleration (g) and Logstandard Deviation (Beta)							
	Slight		Moderate		Extensive		Complete	
	Median	Beta	Median	Beta	Median	Beta	Median	Beta
W1	0.20	0.72	0.40	0.70	0.80	0.67	1.60	0.67
W2	0.20	0.66	0.40	0.67	0.80	0.65	1.60	0.65
S1L	0.20	0.66	0.40	0.68	0.80	0.68	1.60	0.68
S1M	0.20	0.66	0.40	0.68	0.80	0.68	1.60	0.68
S1H	0.20	0.68	0.40	0.68	0.80	0.68	1.60	0.68
S2L	0.20	0.65	0.40	0.68	0.80	0.68	1.60	0.68
S2M	0.20	0.65	0.40	0.68	0.80	0.68	1.60	0.68
S2H	0.20	0.65	0.40	0.67	0.80	0.67	1.60	0.67
S3	0.20	0.65	0.40	0.68	0.80	0.68	1.60	0.68
S4L	0.20	0.66	0.40	0.68	0.80	0.68	1.60	0.68
S4M	0.20	0.65	0.40	0.68	0.80	0.68	1.60	0.68
S4H	0.20	0.66	0.40	0.68	0.80	0.68	1.60	0.68
S5L	0.20	0.65	0.40	0.68	0.80	0.68	1.60	0.68
S5M	0.20	0.65	0.40	0.68	0.80	0.68	1.60	0.68
S5H	0.20	0.65	0.40	0.68	0.80	0.68	1.60	0.68
C1L	0.20	0.66	0.40	0.68	0.80	0.68	1.60	0.68
C1M	0.20	0.66	0.40	0.68	0.80	0.68	1.60	0.68
C1H	0.20	0.68	0.40	0.68	0.80	0.68	1.60	0.68
C2L	0.20	0.65	0.40	0.67	0.80	0.67	1.60	0.67
C2M	0.20	0.64	0.40	0.67	0.80	0.67	1.60	0.67
C2H	0.20	0.65	0.40	0.67	0.80	0.67	1.60	0.67
C3L	0.20	0.65	0.40	0.68	0.80	0.68	1.60	0.68
C3M	0.20	0.64	0.40	0.67	0.80	0.67	1.60	0.67
C3H	0.20	0.65	0.40	0.67	0.80	0.67	1.60	0.67
PC1	0.20	0.67	0.40	0.66	0.80	0.66	1.60	0.66
PC2L	0.20	0.65	0.40	0.68	0.80	0.68	1.60	0.68
PC2M	0.20	0.65	0.40	0.68	0.80	0.68	1.60	0.68
PC2H	0.20	0.66	0.40	0.67	0.80	0.67	1.60	0.67
RM1L	0.20	0.66	0.40	0.67	0.80	0.66	1.60	0.66
RM1M	0.20	0.64	0.40	0.66	0.80	0.65	1.60	0.65
RM2L	0.20	0.66	0.40	0.67	0.80	0.67	1.60	0.67
RM2M	0.20	0.64	0.40	0.66	0.80	0.66	1.60	0.66
RM2H	0.20	0.65	0.40	0.67	0.80	0.67	1.60	0.67
URML	0.20	0.69	0.40	0.65	0.80	0.65	1.60	0.65
URMM	0.20	0.64	0.40	0.66	0.80	0.66	1.60	0.66
MH	0.20	0.67	0.40	0.65	0.80	0.65	1.60	0.65

5.4.4 Structural Fragility Curves - Equivalent Peak Ground Acceleration

Structural damage functions are expressed in terms of an equivalent value of PGA (rather than spectral displacement) for evaluation of buildings that are components of lifelines. Only structural damage functions are developed based on PGA, since structural damage is considered the most appropriate measure of damage for lifeline facilities. Similar methods could be used to develop nonstructural damage functions based on PGA. In this case, capacity curves are not necessary to estimate building response and PGA is used directly as the PESH input to building fragility curves. This section develops equivalent-PGA fragility curves based on the structural damage functions of Tables 5.9a - 5.9d and standard spectrum shape properties of Chapter 4.

Median values of equivalent-PGA fragility curves are based on median values of spectral displacement of the damage state of interest and an assumed demand spectrum shape that relates spectral response to PGA. As such, median values of equivalent PGA are very sensitive to the shape assumed for the demand spectrum (i.e., PESH-input spectrum reduced for damping greater than 5% of critical as described in Section 5.6.2.1). Spectrum shape is influenced by earthquake source (i.e., WUS vs. CEUS attenuation functions), earthquake magnitude (e.g., large vs. small magnitude events), distance from source to site, site conditions (e.g., soil vs. rock) and effective damping which varies based on building properties and earthquake duration (e.g., Short, Moderate or Long duration).

It is not practical to create equivalent-PGA fragility curves for all possible factors that influence demand spectrum shape. Rather, equivalent-PGA fragility curves are developed for a single set of spectrum shape factors (reference spectrum), and a formula is provided for modifying damage state medians to approximate other spectrum shapes. The reference spectrum represents ground shaking of a large-magnitude (i.e., **M** ≅ 7.0) western United States (WUS) earthquake for soil sites (e.g., Site Class D) at site-to-source distances of 15 km, or greater. The demand spectrum based on these assumptions is scaled uniformly at each period such that the spectrum intersects the building capacity curve at the spectral displacement of the median value of the damage state of interest. The PGA of the scaled demand spectrum defines the median value of equivalent-PGA fragility. Figure 5.6 illustrates this scaling and intersection process for a typical building capacity curve and Slight, Moderate, Extensive and Complete structural damage states.

The total variability of each equivalent-PGA structural damage state, β_{SPGA}, is modeled by the combination of following two contributors to damage variability:

- uncertainty in the damage-state threshold of the structural system ($\beta_{M(SPGA)}$ = 0.4 for all building types and damage states),
- variability in response due to the spatial variability of ground motion demand ($\beta_{D(V)}$ = 0.5 for long-period spectral response).

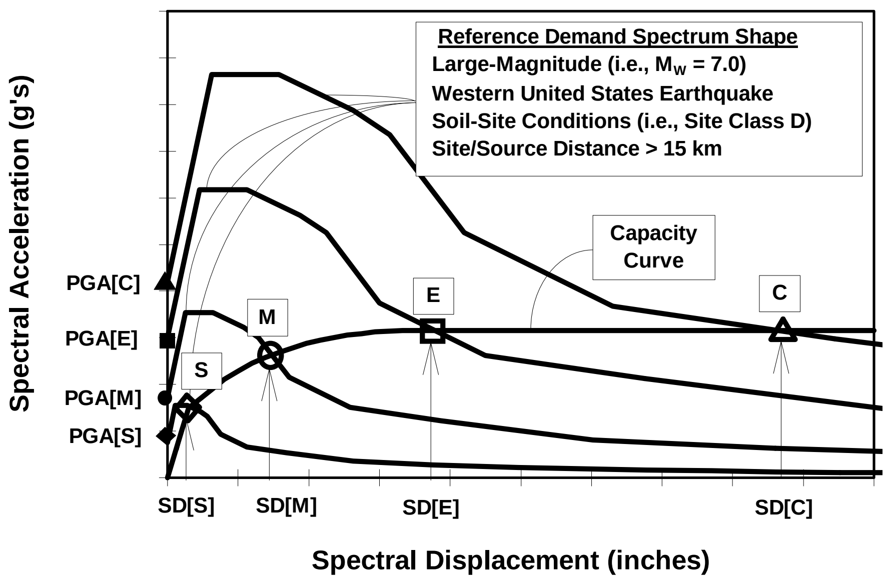


Figure 5.6 Development of Equivalent-PGA Median Damage Values.

The two contributors to damage state variability are assumed to be lognormally distributed, independent random variables and the total variability is simply the square-root-sum-of-the-squares combination of individual variability terms (i.e., β_{SPGA} = 0.64). Tables 5.16a, 5.16b, 5.16c and 5.16d summarize median and lognormal standard deviation (β_{SPGA}) values for Slight, Moderate, Extensive and Complete PGA-based structural damage states for High-Code, Moderate-Code, Low-Code and Pre-Code buildings, respectively.

The values given in Tables 5.16a through 5.16d are appropriate for use in the evaluation of scenario earthquakes whose demand spectrum shape is based on, or similar to, large-magnitude, WUS ground shaking at soil sites (reference spectrum shape). For evaluation of building damage due to scenario earthquakes whose spectra are not similar to the reference spectrum shape, damage-state median parameters may be adjusted to better represent equivalent-PGA structural fragility for the spectrum shape of interest. This adjustment is based on: (1) site condition (if different from Site Class D) and (2) the ratio of long-period spectral response (i.e., S_{A1}) to PGA (if different from a value of 1.5, the ratio of S_{A1} to PGA of the reference spectrum shape). Damage-state variability is not adjusted assuming that the variability associated with ground shaking (although different for different source/site conditions) when combined with the uncertainty in damage-state threshold, is approximately the same for all demand spectrum shapes.

Tables 4.2 and 4.3 provide spectral acceleration response factors for WUS rock (Site Class B) and CEUS rock (Site Class B) locations, respectively. These tables are based on the default WUS and CEUS attenuation functions and describe response ratios, S_{AS}/PGA and S_{AS}/S_{A1}, as a function of distance and earthquake magnitude. Although both short-period response (S_{AS}) and long-period response (S_{A1}) can influence building fragility, long-period response typically dominates building fragility and is the parameter used to relate spectral demand to PGA. Spectral response factors given in Tables 4.2 and 4.3 are combined to form ratios of PGA/S_{A1} as given in Table 5.14 and Table 5.15, respectively, for different earthquake magnitudes and source/site distances.

Table 5.14 Spectrum Shape Ratio, $R_{PGA/SA1}$ - WUS Rock (Site Class B)

Closest Distance to Fault Rupture	PGA/S_{A1} given Magnitude, M:			
	≤ 5	6	7	≥ 8
≤ 10 km	3.8	2.1	1.5	0.85
20 km	3.3	1.8	1.2	0.85
40 km	2.9	1.6	1.05	0.80
≥ 80 km	3.2	1.7	1.0	0.75

Table 5.15 Spectrum Shape Ratio, $R_{PGA/SA1}$ - CEUS Rock (Site Class B)

Hypocentral Distance	PGA/S_{A1} given Magnitude, M:			
	≤ 5	6	7	≥ 8
≤ 10 km	7.8	3.5	2.1	1.1
20 km	8.1	3.1	2.1	1.7
40 km	6.1	2.6	1.8	1.6
≥ 80 km	4.3	1.9	1.4	1.3

Equivalent-PGA medians specified in Tables 5.16a through 5.16d for the reference spectrum shape are converted to medians representing other spectrum shapes using the ratios of Tables 5.14 and 5.15, the soil amplification factor, F_V, and Equation (5-6):

$$\overline{PGA}_{ds} = \overline{PGA}_{R,ds} \cdot R_{PGA/SA1} \cdot \left(\frac{1.5}{F_V}\right) \quad (5\text{-}6)$$

where:

$\overline{PGA}_{ds}$ is the median PGA of structural damage state, ds,

$\overline{PGA}_{R,ds}$ is the median PGA of structural damage state, ds, as given in Tables 5-13a through 5-13d for the reference spectrum shape

$R_{PGA/SA1}$ is the spectrum shape ratio, given in Tables 5.14 - 5.15, and

F_V is the soil amplification factor, given in Table 4.10

In general, implementation of Equation (5-6) requires information on earthquake magnitude and source-to-site distance to estimate the spectrum shape ratio for rock sites, and 1-second period spectral acceleration at the site (to estimate the soil amplification factor). Note that for Tables 5.16a through 5.16d, shaded boxes indicate types that are not permitted by current seismic codes.

Table 5.16a Equivalent-PGA Structural Fragility -
High-Code Seismic Design Level

Building Type	Median Equivalent-PGA (g) and Logstandard Deviation (Beta)							
	Slight		Moderate		Extensive		Complete	
	Median	Beta	Median	Beta	Median	Beta	Median	Beta
W1	0.26	0.64	0.55	0.64	1.28	0.64	2.01	0.64
W2	0.26	0.64	0.56	0.64	1.15	0.64	2.08	0.64
S1L	0.19	0.64	0.31	0.64	0.64	0.64	1.49	0.64
S1M	0.14	0.64	0.26	0.64	0.62	0.64	1.43	0.64
S1H	0.10	0.64	0.21	0.64	0.52	0.64	1.31	0.64
S2L	0.24	0.64	0.41	0.64	0.76	0.64	1.46	0.64
S2M	0.14	0.64	0.27	0.64	0.73	0.64	1.62	0.64
S2H	0.11	0.64	0.22	0.64	0.65	0.64	1.60	0.64
S3	0.15	0.64	0.26	0.64	0.54	0.64	1.00	0.64
S4L	0.24	0.64	0.39	0.64	0.71	0.64	1.33	0.64
S4M	0.16	0.64	0.28	0.64	0.73	0.64	1.56	0.64
S4H	0.13	0.64	0.25	0.64	0.69	0.64	1.63	0.64
S5L								
S5M								
S5H								
C1L	0.21	0.64	0.35	0.64	0.70	0.64	1.37	0.64
C1M	0.15	0.64	0.27	0.64	0.73	0.64	1.61	0.64
C1H	0.11	0.64	0.22	0.64	0.62	0.64	1.35	0.64
C2L	0.24	0.64	0.45	0.64	0.90	0.64	1.55	0.64
C2M	0.17	0.64	0.36	0.64	0.87	0.64	1.95	0.64
C2H	0.12	0.64	0.29	0.64	0.82	0.64	1.87	0.64
C3L								
C3M								
C3H								
PC1	0.20	0.64	0.35	0.64	0.72	0.64	1.25	0.64
PC2L	0.24	0.64	0.36	0.64	0.69	0.64	1.23	0.64
PC2M	0.17	0.64	0.29	0.64	0.67	0.64	1.51	0.64
PC2H	0.12	0.64	0.23	0.64	0.63	0.64	1.49	0.64
RM1L	0.30	0.64	0.46	0.64	0.93	0.64	1.57	0.64
RM1M	0.20	0.64	0.37	0.64	0.81	0.64	1.90	0.64
RM2L	0.26	0.64	0.42	0.64	0.87	0.64	1.49	0.64
RM2M	0.17	0.64	0.33	0.64	0.75	0.64	1.83	0.64
RM2H	0.12	0.64	0.24	0.64	0.67	0.64	1.78	0.64
URML								
URMM								
MH	0.11	0.64	0.18	0.64	0.31	0.64	0.60	0.64

Table 5.16b Equivalent-PGA Structural Fragility - Moderate-Code Seismic Design Level

Building Type	Median Equivalent-PGA (g) and Logstandard Deviation (Beta)							
	Slight		Moderate		Extensive		Complete	
	Median	Beta	Median	Beta	Median	Beta	Median	Beta
W1	0.24	0.64	0.43	0.64	0.91	0.64	1.34	0.64
W2	0.20	0.64	0.35	0.64	0.64	0.64	1.13	0.64
S1L	0.15	0.64	0.22	0.64	0.42	0.64	0.80	0.64
S1M	0.13	0.64	0.21	0.64	0.44	0.64	0.82	0.64
S1H	0.10	0.64	0.18	0.64	0.39	0.64	0.78	0.64
S2L	0.20	0.64	0.26	0.64	0.46	0.64	0.84	0.64
S2M	0.14	0.64	0.22	0.64	0.53	0.64	0.97	0.64
S2H	0.11	0.64	0.19	0.64	0.49	0.64	1.02	0.64
S3	0.13	0.64	0.19	0.64	0.33	0.64	0.60	0.64
S4L	0.19	0.64	0.26	0.64	0.41	0.64	0.78	0.64
S4M	0.14	0.64	0.22	0.64	0.51	0.64	0.92	0.64
S4H	0.12	0.64	0.21	0.64	0.51	0.64	0.97	0.64
S5L								
S5M								
S5H								
C1L	0.16	0.64	0.23	0.64	0.41	0.64	0.77	0.64
C1M	0.13	0.64	0.21	0.64	0.49	0.64	0.89	0.64
C1H	0.11	0.64	0.18	0.64	0.41	0.64	0.74	0.64
C2L	0.18	0.64	0.30	0.64	0.49	0.64	0.87	0.64
C2M	0.15	0.64	0.26	0.64	0.55	0.64	1.02	0.64
C2H	0.12	0.64	0.23	0.64	0.57	0.64	1.07	0.64
C3L								
C3M								
C3H								
PC1	0.18	0.64	0.24	0.64	0.44	0.64	0.71	0.64
PC2L	0.18	0.64	0.25	0.64	0.40	0.64	0.74	0.64
PC2M	0.15	0.64	0.21	0.64	0.45	0.64	0.86	0.64
PC2H	0.12	0.64	0.19	0.64	0.46	0.64	0.90	0.64
RM1L	0.22	0.64	0.30	0.64	0.50	0.64	0.85	0.64
RM1M	0.18	0.64	0.26	0.64	0.51	0.64	1.03	0.64
RM2L	0.20	0.64	0.28	0.64	0.47	0.64	0.81	0.64
RM2M	0.16	0.64	0.23	0.64	0.48	0.64	0.99	0.64
RM2H	0.12	0.64	0.20	0.64	0.48	0.64	1.01	0.64
URML								
URMM								
MH	0.11	0.64	0.18	0.64	0.31	0.64	0.60	0.64

Table 5.16c Equivalent-PGA Structural Fragility - Low-Code Seismic Design Level

Building Type	Median Equivalent-PGA (g) and Logstandard Deviation (Beta)							
	Slight		Moderate		Extensive		Complete	
	Median	Beta	Median	Beta	Median	Beta	Median	Beta
W1	0.20	0.64	0.34	0.64	0.61	0.64	0.95	0.64
W2	0.14	0.64	0.23	0.64	0.48	0.64	0.75	0.64
S1L	0.12	0.64	0.17	0.64	0.30	0.64	0.48	0.64
S1M	0.12	0.64	0.18	0.64	0.29	0.64	0.49	0.64
S1H	0.10	0.64	0.15	0.64	0.28	0.64	0.48	0.64
S2L	0.13	0.64	0.17	0.64	0.30	0.64	0.50	0.64
S2M	0.12	0.64	0.18	0.64	0.35	0.64	0.58	0.64
S2H	0.11	0.64	0.17	0.64	0.36	0.64	0.63	0.64
S3	0.10	0.64	0.13	0.64	0.20	0.64	0.38	0.64
S4L	0.13	0.64	0.16	0.64	0.26	0.64	0.46	0.64
S4M	0.12	0.64	0.17	0.64	0.31	0.64	0.54	0.64
S4H	0.12	0.64	0.17	0.64	0.33	0.64	0.59	0.64
S5L	0.13	0.64	0.17	0.64	0.28	0.64	0.45	0.64
S5M	0.11	0.64	0.18	0.64	0.34	0.64	0.53	0.64
S5H	0.10	0.64	0.18	0.64	0.35	0.64	0.58	0.64
C1L	0.12	0.64	0.15	0.64	0.27	0.64	0.45	0.64
C1M	0.12	0.64	0.17	0.64	0.32	0.64	0.54	0.64
C1H	0.10	0.64	0.15	0.64	0.27	0.64	0.44	0.64
C2L	0.14	0.64	0.19	0.64	0.30	0.64	0.52	0.64
C2M	0.12	0.64	0.19	0.64	0.38	0.64	0.63	0.64
C2H	0.11	0.64	0.19	0.64	0.38	0.64	0.65	0.64
C3L	0.12	0.64	0.17	0.64	0.26	0.64	0.44	0.64
C3M	0.11	0.64	0.17	0.64	0.32	0.64	0.51	0.64
C3H	0.09	0.64	0.16	0.64	0.33	0.64	0.53	0.64
PC1	0.13	0.64	0.17	0.64	0.25	0.64	0.45	0.64
PC2L	0.13	0.64	0.15	0.64	0.24	0.64	0.44	0.64
PC2M	0.11	0.64	0.16	0.64	0.31	0.64	0.52	0.64
PC2H	0.11	0.64	0.16	0.64	0.31	0.64	0.55	0.64
RM1L	0.16	0.64	0.20	0.64	0.29	0.64	0.54	0.64
RM1M	0.14	0.64	0.19	0.64	0.35	0.64	0.63	0.64
RM2L	0.14	0.64	0.18	0.64	0.28	0.64	0.51	0.64
RM2M	0.12	0.64	0.17	0.64	0.34	0.64	0.60	0.64
RM2H	0.11	0.64	0.17	0.64	0.35	0.64	0.62	0.64
URML	0.14	0.64	0.20	0.64	0.32	0.64	0.46	0.64
URMM	0.10	0.64	0.16	0.64	0.27	0.64	0.46	0.64
MH	0.11	0.64	0.18	0.64	0.31	0.64	0.60	0.64

Table 5.16d Equivalent-PGA Structural Fragility -
Pre-Code Seismic Design Level

Building Type	Median Equivalent-PGA (g) and Logstandard Deviation (Beta)							
	Slight		Moderate		Extensive		Complete	
	Median	Beta	Median	Beta	Median	Beta	Median	Beta
W1	0.18	0.64	0.29	0.64	0.51	0.64	0.77	0.64
W2	0.12	0.64	0.19	0.64	0.37	0.64	0.60	0.64
S1L	0.09	0.64	0.13	0.64	0.22	0.64	0.38	0.64
S1M	0.09	0.64	0.14	0.64	0.23	0.64	0.39	0.64
S1H	0.08	0.64	0.12	0.64	0.22	0.64	0.38	0.64
S2L	0.11	0.64	0.14	0.64	0.23	0.64	0.39	0.64
S2M	0.10	0.64	0.14	0.64	0.28	0.64	0.47	0.64
S2H	0.09	0.64	0.13	0.64	0.29	0.64	0.50	0.64
S3	0.08	0.64	0.10	0.64	0.16	0.64	0.30	0.64
S4L	0.10	0.64	0.13	0.64	0.20	0.64	0.36	0.64
S4M	0.09	0.64	0.13	0.64	0.25	0.64	0.43	0.64
S4H	0.09	0.64	0.14	0.64	0.27	0.64	0.47	0.64
S5L	0.11	0.64	0.14	0.64	0.22	0.64	0.37	0.64
S5M	0.09	0.64	0.14	0.64	0.28	0.64	0.43	0.64
S5H	0.08	0.64	0.14	0.64	0.29	0.64	0.46	0.64
C1L	0.10	0.64	0.12	0.64	0.21	0.64	0.36	0.64
C1M	0.09	0.64	0.13	0.64	0.26	0.64	0.43	0.64
C1H	0.08	0.64	0.12	0.64	0.21	0.64	0.35	0.64
C2L	0.11	0.64	0.15	0.64	0.24	0.64	0.42	0.64
C2M	0.10	0.64	0.15	0.64	0.30	0.64	0.50	0.64
C2H	0.09	0.64	0.15	0.64	0.31	0.64	0.52	0.64
C3L	0.10	0.64	0.14	0.64	0.21	0.64	0.35	0.64
C3M	0.09	0.64	0.14	0.64	0.25	0.64	0.41	0.64
C3H	0.08	0.64	0.13	0.64	0.27	0.64	0.43	0.64
PC1	0.11	0.64	0.14	0.64	0.21	0.64	0.35	0.64
PC2L	0.10	0.64	0.13	0.64	0.19	0.64	0.35	0.64
PC2M	0.09	0.64	0.13	0.64	0.24	0.64	0.42	0.64
PC2H	0.09	0.64	0.13	0.64	0.25	0.64	0.43	0.64
RM1L	0.13	0.64	0.16	0.64	0.24	0.64	0.43	0.64
RM1M	0.11	0.64	0.15	0.64	0.28	0.64	0.50	0.64
RM2L	0.12	0.64	0.15	0.64	0.22	0.64	0.41	0.64
RM2M	0.10	0.64	0.14	0.64	0.26	0.64	0.47	0.64
RM2H	0.09	0.64	0.13	0.64	0.27	0.64	0.50	0.64
URML	0.13	0.64	0.17	0.64	0.26	0.64	0.37	0.64
URMM	0.09	0.64	0.13	0.64	0.21	0.64	0.38	0.64
MH	0.08	0.64	0.11	0.64	0.18	0.64	0.34	0.64

5.5 Building Damage Due to Ground Failure

5.5.1 Overview

Building damage is characterized by four damage states (i.e., Slight, Moderate, Extensive and Complete). These four states are simplified for ground failure to include only one combined Extensive/Complete damage state. In essence, buildings are assumed to be either undamaged or severely damaged due to ground failure. In fact, Slight or Moderate damage can occur due to ground failure, but the likelihood of this damage is considered to be small (relative to ground shaking damage) and tacitly included in predictions of Slight or Moderate damage due to ground shaking.

Given the earthquake demand in terms of permanent ground deformation (PGD), the probability of being in the Extensive/Complete damage state is estimated using fragility curves of a form similar to those used to estimate shaking damage. Separate fragility curves distinguish between ground failure due to lateral spreading and ground failure due to ground settlement, and between shallow and deep foundations.

5.5.2 Fragility Curves - Peak Ground Displacement

There is no available relationship between the likelihood of Extensive/Complete damage of buildings and PGD. Engineering judgment is used to develop a set of assumptions, which define building fragility. These assumptions are shown in Table 5.17 for buildings with shallow foundations (e.g., spread footings).

Table 5.17 Building Damage Relationship to PGD - Shallow Foundations

$P[E \text{ or } C \mid PGD]$	Settlement PGD (inches)	Lateral Spread PGD (inches)
0.1	2	12
0.5 (median)	10	60

The above assumptions are based on the expectation that about 10 (i.e., 8 Extensive damage, 2 Complete damage) out of 100 buildings on spread footings would be severely damaged for 2 inches of settlement PGD or 12 inches of lateral spread PGD, and that about 50 (i.e., 40 Extensive damage, 10 Complete damage) out of 100 buildings on spread footings would be severely damaged for 10 inches of settlement PGD or 60 inches of lateral spread PGD. Lateral spread is judged to require significantly more PGD to effect severe damage than ground settlement. Many buildings in lateral spread areas are expected to move with the spread, but not to be severely damaged until the spread becomes quite significant.

Median PGD values given in the Table 5.17 are used with a lognormal standard deviation value of $\beta_{PGD} = 1.2$ to estimate P[E or C|PGD] for buildings on shallow foundations or buildings of unknown foundation type. The value of $\beta_{PGD} = 1.2$ is based on the factor of 5 between the PGD values at the 10 and 50 percentile levels.

No attempt is made to distinguish damage based on building type, since model building descriptions do not include foundation type. Foundation type is critical to PGD performance and buildings on deep foundations (e.g., piles) perform much better than buildings on spread footings, if the ground settles. When the building is known to be supported by a deep foundation, the probability of Extensive or Complete damage is reduced by a factor of 10 from that predicted for settlement-induced damage of the same building on a shallow foundation. Deep foundations will improve building performance by only a limited amount, if ground spreads laterally. When the building is known to be supported by a deep foundation, the probability of Extensive or Complete damage is reduced by a factor of 2 from that predicted for spread-induced damage of the same building on a shallow foundation.

5.6 Evaluation of Building Damage

5.6.1 Overview

During an earthquake, the building may be damaged either by ground shaking, ground failure, or both. Buildings are evaluated separately for the two modes of failure the resulting damage-state probabilities are combined for evaluation of loss.

5.6.2 Damage Due to Ground Shaking

This section describes the process of developing damage state probabilities based on structural and nonstructural fragility curves, model building capacity curves and a demand spectrum. Building response (e.g., peak displacement) is determined by the intersection of the demand spectrum and the building capacity curve. The demand spectrum is based on the PESH input spectrum reduced for effective damping (when effective damping exceeds the 5% damping level of the PESH input spectrum).

5.6.2.1 Demand Spectrum Reduction for Effective Damping

The elastic response spectra provided as a PESH input apply only to buildings that remain elastic during the entire ground shaking time history and have elastic damping values equal to 5% of critical. This is generally not true on both accounts. Therefore, two modifications are made to elastic response spectra: (a) demand spectra are modified for buildings with elastic damping not equal to 5%, and (b) demand spectra are modified for the hysteretic energy dissipated by buildings "pushed" beyond their elastic limits. Modifications are represented by reduction factors by which the spectral ordinates are divided to obtain the damped demand spectra.

Extensive work has been published in the past two decades on the effect of damping and/or energy dissipation on spectral demand. The Methodology reduces demand spectra for effective damping greater than 5% based on statistically-based formulas of Newmark and Hall (1982). Other methods are available for estimating spectral reduction factors based on statistics relating reduction to ductility demand. It is believed that both methods yield the same results for most practical purposes (FEMA 273). Newmark and Hall provide formulas for construction of elastic response spectra at different damping ratios, B (expressed as a percentage). These formulas represent all site classes (soil types) distinguishing between domains of constant acceleration and constant velocity. Ratios of these formulas are used to develop an acceleration-domain (short-period) reduction factor, R_A, and a velocity-domain (1-second spectral acceleration) reduction factor, R_V, for modification of 5%-damped, elastic response spectra (PESH input). These reduction factors are based on effective damping, B_{eff}, as given in Equations (5-7) and (5-8) below:

$$R_A = 2.12 \big/ \left(3.21 - 0.68\ln(B_{eff})\right) \tag{5-7}$$

$$R_V = 1.65 \big/ \left(2.31 - 0.41\ln(B_{eff})\right) \tag{5-8}$$

for which effective damping is defined as the sum of elastic damping, B_E, and hysteretic damping, B_H:

$$B_{eff} = B_E + B_H \tag{5-9}$$

Elastic damping, B_E, is dependent on structure type and is based on the recommendations of Newmark & Hall for materials at or just below their yield point. Hysteretic damping, B_H, is dependent on the amplitude of response and is based on the area enclosed by the hysteresis loop, considering potential degradation of energy-absorption capacity of the structure during cyclic earthquake load. Effective damping, B_{eff}, is also a function of the amplitude of response (e.g., peak displacement), as expressed in Equation (5-10):

$$B_{eff} = B_E + \kappa \cdot \left(\frac{\text{Area}}{2\pi \cdot D \cdot A} \right) \tag{5-10}$$

where:

- B_E is the elastic (pre-yield) damping of the model building type
- Area is the area enclosed by the hysteresis loop, as defined by a symmetrical push-pull of the building capacity curve up to peak positive and negative displacements, $\pm$ D
- D is the peak displacement response of the push-over curve,
- A is the peak acceleration response at peak displacement, D
- κ is a degradation factor that defines the effective amount of hysteretic damping as a function of earthquake duration, as specified in Table 5.18.

Table 5.18 Degradation Factor (κ) as a Function of Short, Moderate and Long Earthquake

Building Type		High-Code Design			Moderate-Code Design			Low-Code Design			Pre-Code Design		
No.	Label	Short	Moderate	Long	Short	Moderate	Long	Short	Moderate	Long	Short	Moderate	Long
1	W1	1.00	0.80	0.50	0.90	0.60	0.30	0.70	0.40	0.20	0.50	0.30	0.10
2	W2	0.90	0.60	0.40	0.80	0.40	0.20	0.60	0.30	0.10	0.40	0.20	0.00
3	S1L	0.90	0.60	0.40	0.80	0.40	0.20	0.60	0.30	0.10	0.40	0.20	0.00
4	S1M	0.90	0.60	0.40	0.80	0.40	0.20	0.60	0.30	0.10	0.40	0.20	0.00
5	S1H	0.90	0.60	0.40	0.80	0.40	0.20	0.60	0.30	0.10	0.40	0.20	0.00
6	S2L	0.70	0.50	0.30	0.60	0.40	0.20	0.50	0.30	0.10	0.40	0.20	0.00
7	S2M	0.70	0.50	0.30	0.60	0.40	0.20	0.50	0.30	0.10	0.40	0.20	0.00
8	S2H	0.70	0.50	0.30	0.60	0.40	0.20	0.50	0.30	0.10	0.40	0.20	0.00
9	S3	0.70	0.50	0.30	0.60	0.40	0.20	0.50	0.30	0.10	0.40	0.20	0.00
10	S4L	0.70	0.50	0.30	0.60	0.40	0.20	0.50	0.30	0.10	0.40	0.20	0.00
11	S4M	0.70	0.50	0.30	0.60	0.40	0.20	0.50	0.30	0.10	0.40	0.20	0.00
12	S4H	0.70	0.50	0.30	0.60	0.40	0.20	0.50	0.30	0.10	0.40	0.20	0.00
13	S5L	0.50	0.30	0.10	0.50	0.30	0.10	0.50	0.30	0.10	0.40	0.20	0.00
14	S5M	0.50	0.30	0.10	0.50	0.30	0.10	0.50	0.30	0.10	0.40	0.20	0.00
15	S5H	0.50	0.30	0.10	0.50	0.30	0.10	0.50	0.30	0.10	0.40	0.20	0.00
16	C1L	0.90	0.60	0.40	0.80	0.40	0.20	0.60	0.30	0.10	0.40	0.20	0.00
17	C1M	0.90	0.60	0.40	0.80	0.40	0.20	0.60	0.30	0.10	0.40	0.20	0.00
18	C1H	0.90	0.60	0.40	0.80	0.40	0.20	0.60	0.30	0.10	0.40	0.20	0.00
19	C2L	0.90	0.60	0.40	0.80	0.40	0.20	0.60	0.30	0.10	0.40	0.20	0.00
20	C2M	0.90	0.60	0.40	0.80	0.40	0.20	0.60	0.30	0.10	0.40	0.20	0.00
21	C2H	0.90	0.60	0.40	0.80	0.40	0.20	0.60	0.30	0.10	0.40	0.20	0.00
22	C3L	0.50	0.30	0.10	0.50	0.30	0.10	0.50	0.30	0.10	0.40	0.20	0.00
23	C3M	0.50	0.30	0.10	0.50	0.30	0.10	0.50	0.30	0.10	0.40	0.20	0.00
24	C3H	0.50	0.30	0.10	0.50	0.30	0.10	0.50	0.30	0.10	0.40	0.20	0.00
25	PC1	0.70	0.50	0.30	0.60	0.40	0.20	0.50	0.30	0.10	0.40	0.20	0.00
26	PC2L	0.70	0.50	0.30	0.60	0.40	0.20	0.50	0.30	0.10	0.40	0.20	0.00
27	PC2M	0.70	0.50	0.30	0.60	0.40	0.20	0.50	0.30	0.10	0.40	0.20	0.00
28	PC2H	0.70	0.50	0.30	0.60	0.40	0.20	0.50	0.30	0.10	0.40	0.20	0.00
29	RM1L	0.90	0.60	0.40	0.80	0.40	0.20	0.60	0.30	0.10	0.40	0.20	0.00
30	RM1M	0.90	0.60	0.40	0.80	0.40	0.20	0.60	0.30	0.10	0.40	0.20	0.00
31	RM2L	0.90	0.60	0.40	0.80	0.40	0.20	0.60	0.30	0.10	0.40	0.20	0.00
32	RM2M	0.90	0.60	0.40	0.80	0.40	0.20	0.60	0.30	0.10	0.40	0.20	0.00
33	RM2H	0.90	0.60	0.40	0.80	0.40	0.20	0.60	0.30	0.10	0.40	0.20	0.00
34	URML	0.50	0.30	0.10	0.50	0.30	0.10	0.50	0.30	0.10	0.40	0.20	0.00
35	URMM	0.50	0.30	0.10	0.50	0.30	0.10	0.50	0.30	0.10	0.40	0.20	0.00
36	MH	0.80	0.40	0.20	0.80	0.40	0.20	0.80	0.40	0.20	0.60	0.30	0.10

Duration

The Methodology recognizes the importance of the duration of ground shaking on building response by reducing effective damping (i.e., κ factors) as a function of shaking duration. Shaking duration is described qualitatively as either Short, Moderate or Long, and is assumed to be a function of earthquake magnitude (although proximity to fault rupture also influences the duration of ground shaking). For scenario earthquakes of magnitude $\mathbf{M} \leq 5.5$, effective damping is based on the assumption of ground shaking of Short duration. For scenario earthquakes of magnitude $\mathbf{M} \geq 7.5$, effective damping is based on the assumption of ground shaking of Long duration. Effective damping is based on the assumption of Moderate duration for all other earthquake magnitudes (including probabilistic, or other, analyses of unknown magnitude).

Construction of Demand Spectra

Demand spectral acceleration, $S_A[T]$, in units of acceleration (g) is defined by Equation (5-11a) at short periods (acceleration domain), Equation (5-11b) at long periods (velocity domain) and Equation (5-11c) at very long periods (displacement domain).

At short periods, $0 < T \leq T_{AV\beta}$:

$$S_A[T] = S_{ASi} \big/ R_A[B_{eff}] = S_{ASi} \big/ \left(2.12 \big/ \left(3.21 - 0.68\ln\left(B_{eff}\right)\right)\right) \tag{5-11a}$$

At long periods, $T_{AV\beta} < T \leq T_{VD}$:

$$S_A[T] = \left(\frac{S_{A1i}}{T}\right) \Big/ R_V[B_{eff}] = \left(\frac{S_{A1i}}{T}\right) \Big/ \left(1.65 \big/ \left(2.31 - 0.41\ln\left(B_{eff}\right)\right)\right) \tag{5-11b}$$

At very long periods, $T > T_{VD}$:

$$S_A[T] = \left(\frac{S_{A1i} \cdot T_{VD}}{T^2}\right) \Big/ R_V[B_{TVD}] = \left(\frac{S_{A1i} \cdot T_{VD}}{T^2}\right) \Big/ \left(1.65 \big/ \left(2.31 - 0.41\ln\left(B_{TVD}\right)\right)\right) \tag{5-11c}$$

where: S_{ASi} is the 5%-damped, short-period spectral acceleration for Site Class i (in units of g), as defined by Equation (4-5),

S_{A1i} is the 5%-damped, 1-second-period spectral acceleration for Site Class i (units of g), as defined by Equation (4-6), times 1 second,

T_{AVi} is the transition period between 5%-damped constant spectral acceleration and 5%-damped constant spectral velocity for Site Class i (sec.), as defined by Equation (4-7),

B_{TVD} is the value of effective damping at the transition period, T_{VD}, and

B_{TAVB} is the value of effective damping at the transition period, T_{AVB}.

The transition period, T_{AVB}, between acceleration and velocity domains is a function of the effective damping at this period, as defined by Equation (5-12). The transition period, T_{VD}, between velocity and displacement domains is independent of effective damping, as defined by Equation (4-4).

$$T_{AVB} = T_{AVi}\left(\frac{R_A\left[B_{TAVB}\right]}{R_V\left[B_{TAVB}\right]}\right) = T_{AVi}\left(\frac{2.12/\left(3.21-0.68\ln\left(B_{TAVB}\right)\right)}{1.65/\left(2.31-0.41\ln\left(B_{TAVB}\right)\right)}\right) \tag{5-12}$$

Demand spectral displacement, $S_D[T]$, in inches, is based on $S_A[T]$, in units of g, as given on Equation (5-13):

$$S_D[T] = 9.8 \cdot S_A[T] \cdot T^2 \tag{5-13}$$

Figure 5.7 shows typical demand spectra (spectral acceleration plotted as a function of spectral displacement) for three demand levels. These three demand levels represent Short (κ = 0.80), Moderate (κ = 0.40) and Long (κ = 0.20) duration ground shaking, respectively. Also shown in the figure is the building capacity curve of a low-rise building of Moderate-Code seismic design that was used to estimate effective damping. The intersection of the capacity curve with each of the three demand spectra illustrates the significance of duration (damping) on building response.

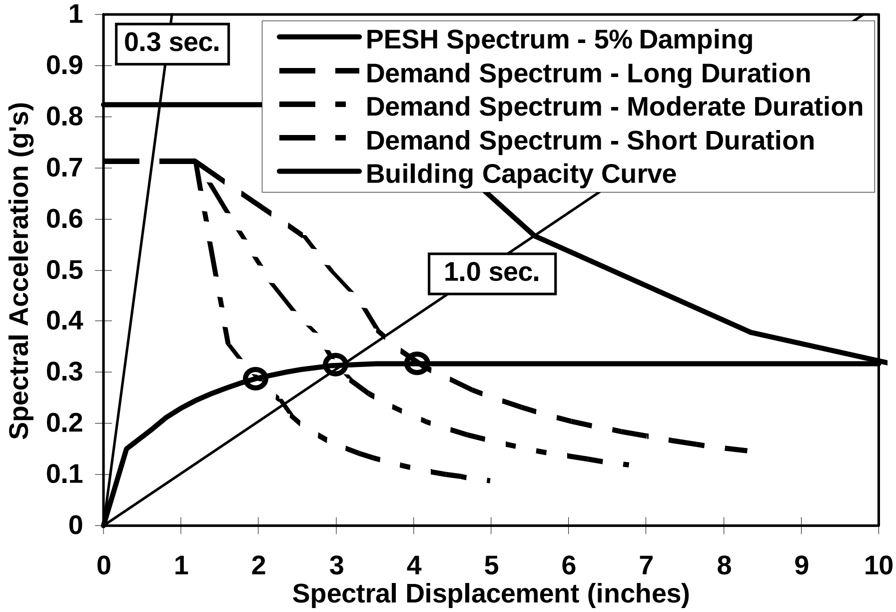


Figure 5.7 Example Demand Spectra - Moderate-Code Building

(M = 7.0 at 20 km, WUS, Site Class E).

5.6.2.2 Damage State Probability

Structural and nonstructural fragility curves are evaluated for spectral displacement and spectral acceleration defined by the intersection of the capacity and demand curves. Each of these curves describes the cumulative probability of being in, or exceeding, a particular damage state. Nonstructural components (both drift- and acceleration-sensitive components) may, in some cases, be dependent on the structural damage state (e.g., Complete structural damage may cause Complete nonstructural damage). The Methodology assumes nonstructural damage states to be independent of structural damage states. Cumulative probabilities are differenced to obtain discrete probabilities of being in each of the five damage states. This process is shown schematically in Figure 5.8.

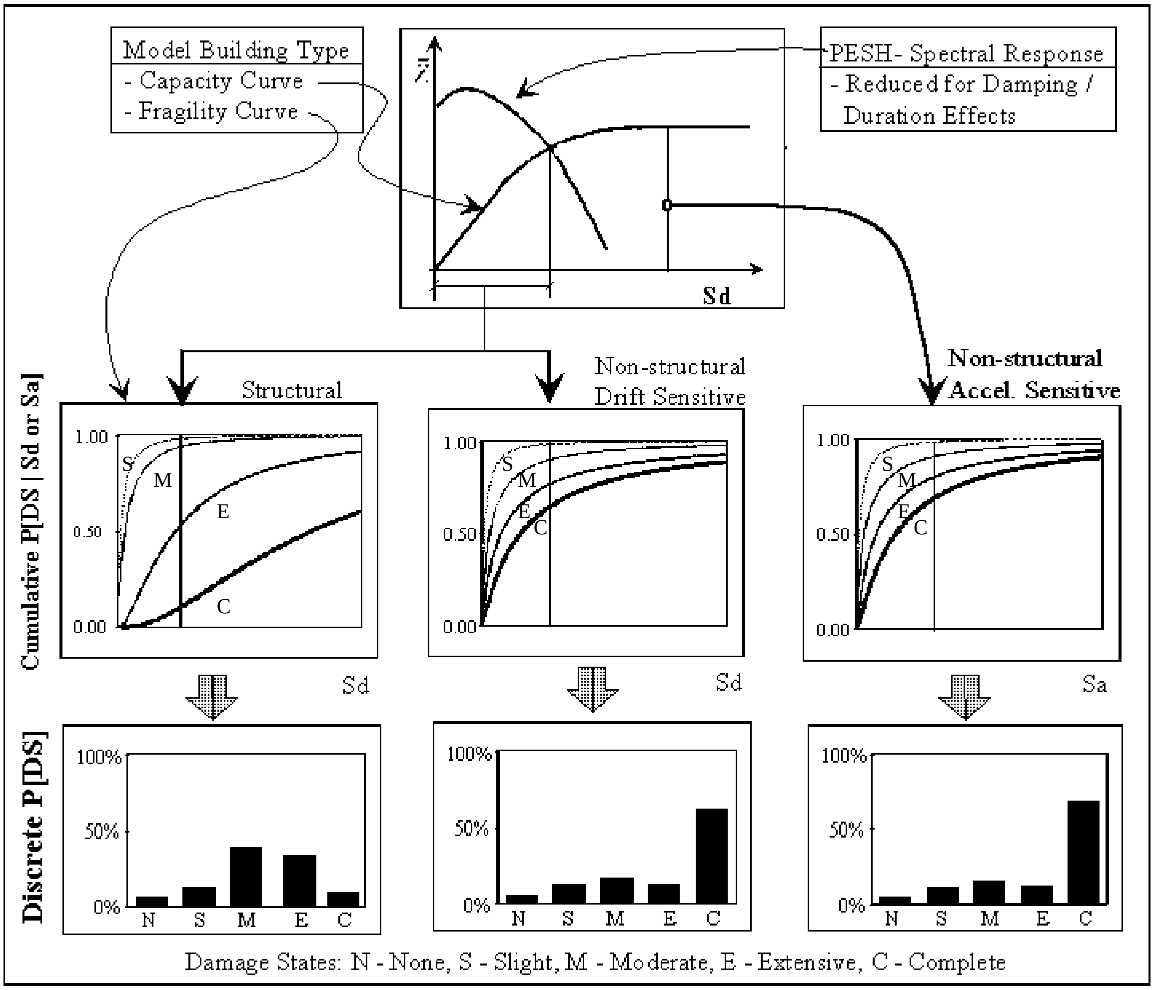


Figure 5.8 Example Building Damage Estimation Process.

It is also meaningful to interpret damage probabilities as the fraction of all buildings (of the same type) that would be in the particular damage state of interest. For example, a 30% probability of Moderate damage may also be thought of as 30 out of 100 buildings (of the same type) being in the Moderate damage state.

5.6.3 Combined Damage Due to Ground Failure and Ground Shaking

This section describes the combination of damage state probabilities due to ground failure (Section 5.5.2) and ground shaking (Section 5.6.2.2). It is assumed that damage due to ground shaking (GS) is independent of damage due to ground failure (GF). Ground failure tends to cause severe damage to buildings and is assumed to contribute only to Extensive and Complete damage states (refer to Section 5.5.1). These assumptions are described by the following formulas:

$$P_{GF}[DS \geq S] = P_{GF}[DS \geq E] \tag{5-14}$$

$$P_{GF}[DS \geq M] = P_{GF}[DS \geq E] \tag{5-15}$$

$$P_{GF}[DS \geq C] = 0.2 \times P_{GF}[DS \geq E] \tag{5-16}$$

The damage state probability (probability of being in or exceeding a given damage state) for GF is assumed to be the maximum of the three types of ground failure (liquefaction, landsliding, and spread). Thus, the combined (due to occurrence of GF or GS) probabilities of being in or exceeding given damage states are:

$$P_{COMB}[DS \geq S] = P_{GF}[DS \geq S] + P_{GS}[DS \geq S] - P_{GF}[DS \geq S] \times P_{GS}[DS \geq S] \tag{5-17}$$

$$P_{COMB}[DS \geq M] = P_{GF}[DS \geq M] + P_{GS}[DS \geq M] - P_{GF}[DS \geq M] \times P_{GS}[DS \geq M] \tag{5-18}$$

$$P_{COMB}[DS \geq E] = P_{GF}[DS \geq E] + P_{GS}[DS \geq E] - P_{GF}[DS \geq E] \times P_{GS}[DS \geq E] \tag{5-19}$$

$$P_{COMB}[DS \geq C] = P_{GF}[DS \geq C] + P_{GS}[DS \geq C] - P_{GF}[DS \geq C] \times P_{GS}[DS \geq C] \tag{5-20}$$

where DS is damage state, and the symbols: S, M, E, and C stand for Slight, Moderate, Extensive, and Complete damage, respectively. COMB indicates the combined probability for the damage state due to occurrence of ground failure or ground shaking. Note that the following condition must always be true:

$$1 \geq P_{COMB}[DS \geq S] \geq P_{COMB}[DS \geq M] \geq P_{COMB}[DS \geq E] \geq P_{COMB}[DS \geq C] \tag{5-21}$$

The discrete probabilities (probabilities of being in a given damage state) are given as:

$$P_{COMB}\left[DS = C\right] = P_{COMB}\left[DS \geq C\right] \quad (5\text{-}22)$$

$$P_{COMB}\left[DS = E\right] = P_{COMB}\left[DS \geq E\right] - P_{COMB}\left[DS \geq C\right] \quad (5\text{-}23)$$

$$P_{COMB}\left[DS = M\right] = P_{COMB}\left[DS \geq M\right] - P_{COMB}\left[DS \geq E\right] \quad (5\text{-}24)$$

$$P_{COMB}\left[DS = S\right] = P_{COMB}\left[DS \geq S\right] - P_{COMB}\left[DS \geq M\right] \quad (5\text{-}25)$$

$$P_{COMB}\left[DS = None\right] = 1 - P_{COMB}\left[DS \geq S\right] \quad (5\text{-}26)$$

5.6.4 Combined Damage to Occupancy Classes

The damage state probabilities for model building types (as estimated from Section 5.6.3) are combined to yield the damage state probabilities of the occupancy classes to which they belong. For each damage state, the probability of damage to each model building type is weighted according to the fraction of the total floor area of that model building type and summed over all building types. This is expressed in equation form:

$$POSTR_{ds,i} = \sum_{j=1}^{36}\left[PMBTSTR_{ds,j} \times \frac{FA_{i,j}}{FA_i}\right] \quad (5\text{-}27)$$

where $PMBTSTR_{ds,j}$ is the probability of the model building type j being in damage state ds. $POSTR_{ds,i}$ is the probability of occupancy class i being in damage state ds. $FA_{i,j}$ indicates the floor area of model building type j in occupancy class i, and FA_i denotes the total floor area of the occupancy class i (refer to Chapter 3 for floor area distributions of model building types by occupancy class). Similarly, the damage-state probabilities for nonstructural components can be estimated.

$$PONSD_{ds,i} = \sum_{j=1}^{36}\left[PMBTNSD_{ds,j} \times \frac{FA_{i,j}}{FA_i}\right] \quad (5\text{-}28)$$

$$PONSA_{ds,i} = \sum_{j=1}^{36}\left[PMBTNSA_{ds,j} \times \frac{FA_{i,j}}{FA_i}\right] \quad (5\text{-}29)$$

where $PMBTNSD_{ds,j}$ and $PMBTNSA_{ds,j}$ refer to the probabilities of model building type j being in nonstructural drift- and acceleration-sensitive damage state ds, respectively; and $PONSD_{ds,i}$ and $PONSA_{ds,i}$ refer to the probabilities of the occupancy class i being the nonstructural drift-sensitive and acceleration-sensitive damage state, ds, respectively. These occupancy class probabilities are used in Chapter 15 to estimate direct economic loss.

5.7 Guidance for Expert Users

This section provides guidance for users who are seismic/structural experts interested in modifying the building damage functions supplied with the methodology. This section also provides the expert user with guidance regarding the selection of the appropriate mix of design levels for the region of interest.

5.7.1 Selection of Representative Seismic Design Level

The methodology permits the user to select the seismic design level considered appropriate for the study region and to define a mix of seismic design levels for each model building type. The building damage functions provided are based on current-Code provisions and represent buildings of modern design and construction. Most buildings in a study region will likely not be of modern design and construction (i.e., do not conform to 1976 *UBC, 1985 NEHRP Provisions*, or later editions of these model Codes). For many study regions, particularly those in the Central and Eastern United States, seismic provisions may not be enforced (or only adopted very recently). Building damage functions for new buildings designed and constructed to meet modern-Code provisions should not be used for older, non-complying buildings.

The building damage functions represent specific cells of a three by three matrix that defines three seismic design levels (High, Moderate and Low) and, for each of these design levels, three seismic performance levels (Inferior, Ordinary and Superior), as shown in Table 5.19. For completeness, cells representing Special buildings of Chapter 6 (Essential Facilities) are also included in the matrix.

Table 5.19 Seismic Design and Performance Levels of Default Building Damage Functions (and Approximate Structural Strength and Ductility)

Seismic Design Level	**Seismic Performance Level**		
	Superior[1]	**Ordinary**	**Inferior**
High **(*UBC* Zone 4)**	Special High-Code *Maximum Strength* *Maximum Ductility*	High-Code *High Strength* *High Ductility*	 *Moderate Strength* *Mod./Low Ductility*
Moderate **(*UBC* Zone 2B)**	Special Moderate-Code *High/Mod. Strength* *High Ductility*	Moderate-Code *Moderate Strength* *Moderate Ductility*	 *Low Strength* *Low Ductility*
Low **(*UBC* Zone 1)**	Special Low-Code *Mod./Low Strength* *Moderate Ductility*	Low-Code *Low Strength* *Low Ductility*	Pre-Code *Minimal Strength* *Minimal Ductility*

1. See Chapter 6 for Special High-Code, Moderate-Code and Low-Code building damage functions.

Table 5.19 also defines the approximate structural strength and ductility attributes of buildings occupying each of the nine cells. The design level is defined by Seismic Zones of the *Uniform*

Building Code (*UBC*), since most buildings in the United States that have been designed for earthquakes used some version of the *UBC.* Table 5.20 relates *UBC* seismic zones to seismic design regions of the *NEHRP Provisions*.

Expert users may tailor the damage functions to their study area of interest by determining the appropriate fraction of each building type that conforms essentially to modern-Code provisions (based on age of construction). Buildings deemed not to conform to modern-Code provisions should be assigned a lower seismic design level, or defined as Pre-Code buildings if not seismically designed. For instance, older buildings located in High-Code seismic design areas should be evaluated using damage functions for either Moderate-Code buildings or Pre-Code buildings, for buildings that pre-date seismic codes. Table 5.20 provides guidance for selecting appropriate building damage functions based on building location (i.e., seismic region) and building age. The years shown as break-off points should be considered very approximate and may not be appropriate for many seismic regions, particularly regions of low and moderate seismicity where seismic codes have not been routinely enforced.

Table 5.20 Guidelines for Selection of Damage Functions for Typical Buildings Based on *UBC* Seismic Zone and Building Age

UBC Seismic Zone (NEHRP Map Area)	Post-1975	1941 - 1975	Pre-1941
Zone 4 **(Map Area 7)**	High-Code	Moderate-Code	Pre-Code (W1 = Moderate-Code)
Zone 3 **(Map Area 6)**	Moderate-Code	Moderate-Code	Pre-Code (W1 = Moderate-Code)
Zone 2B **(Map Area 5)**	Moderate-Code	Low-Code	Pre-Code (W1 = Low-Code)
Zone 2A **(Map Area 4)**	Low-Code	Low-Code	Pre-Code (W1 = Low-Code)
Zone 1 **(Map Area 2/3)**	Low-Code	Pre-Code (W1 = Low-Code)	Pre-Code (W1 = Low-Code)
Zone 0 **(Map Area 1)**	Pre-Code (W1 = Low-Code)	Pre-Code (W1 = Low-Code)	Pre-Code (W1 = Low-Code)

The guidelines given in Table 5.20 assume that buildings in the study region are not designed for wind. The user should consider the possibility that mid-rise and high-rise buildings could be designed for wind and may have considerable lateral strength (though not ductility), even if not designed for earthquake. Users must be knowledgeable about the type and history of construction in the study region of interest and apply engineering judgment in assigning the fraction of each building type to a seismic design group.

5.7.2 Development of Damage Functions for Other Buildings

For a building type other than one of the 36 described in Table 5.1, expert users should select a set of building damage functions that best represents the type of construction, strength and ductility of the building type of interest. Such buildings include rehabilitated structures that have improved seismic capacity. For example, URM (Pre-Code) buildings retrofitted in accordance with Division 88, the Los Angeles City Ordinance to “reduce the risk of life loss,” demonstrated significantly improved seismic performance during the 1994 Northridge earthquake [SSC, 1995]. Structural damage to these buildings would be better estimated using either essential facility damage functions of either Low-Code or Moderate-Code RM1 buildings.

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Chapter 6
Direct Physical Damage - Essential and High Potential Loss Facilities

6.1 Introduction

This chapter describes methods for determining the probability of Slight, Moderate, Extensive and Complete damage to essential facilities. These methods are identical to those of Chapter 5 that describe damage to "Code" buildings, except that certain essential facilities are represented by "Special" building damage functions. Special building damage functions are appropriate for evaluation of essential facilities when the user anticipates above-Code seismic performance for these facilities. The flowchart of the methodology highlighting the essential and high potential loss facility damage components and showing its relationship to other components is shown in Flowchart 6.1.

This chapter also provides guidance for high potential loss (HPL) facilities. The methodology highlighting the Direct Physical Damage is shown in Flowchart 6.1.

6.1.1 Scope

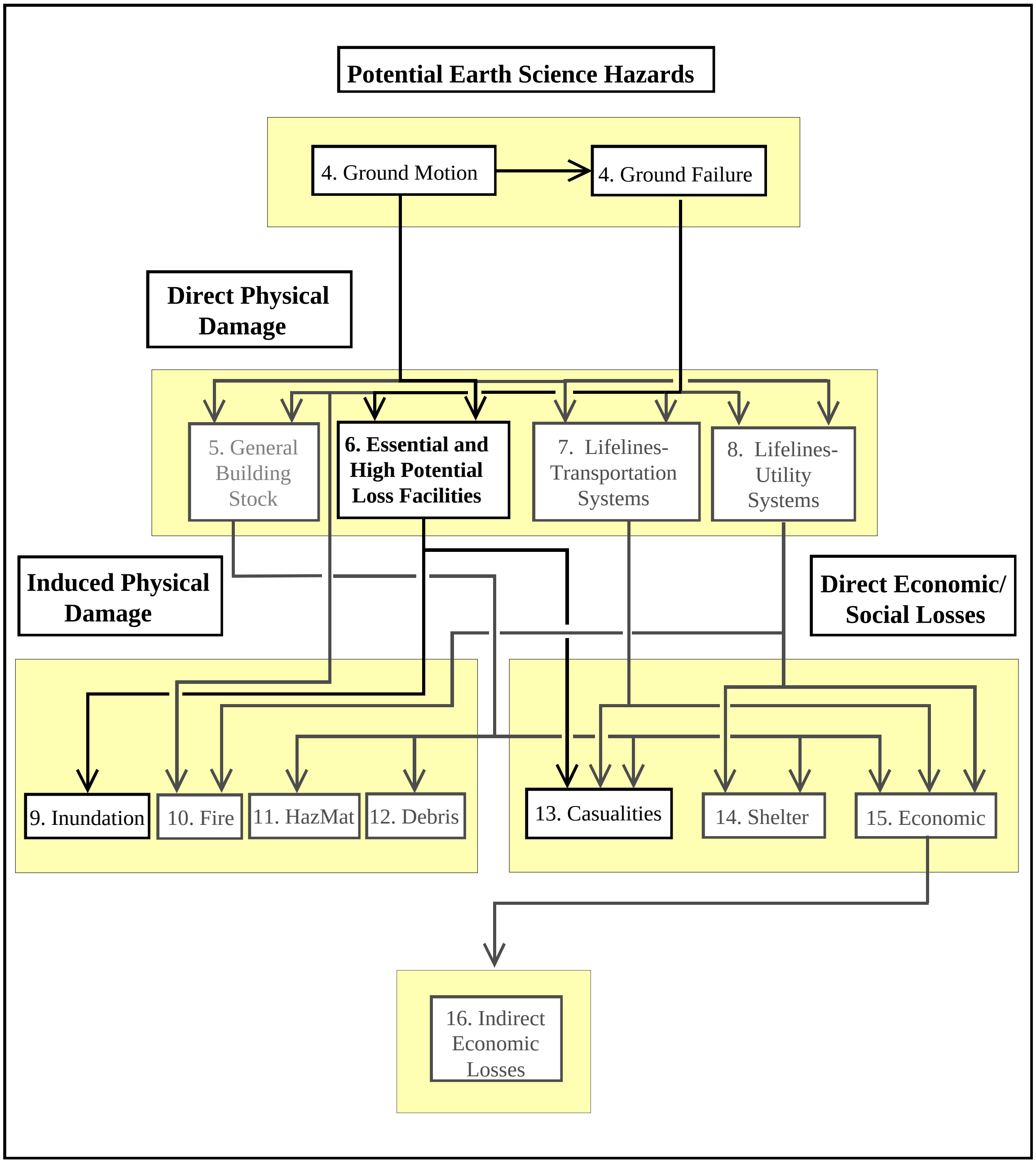
The scope of this chapter includes: (1) classification of essential facilities, (2) building damage functions for Special buildings, (3) methods for estimation of earthquake damage to essential facilities, given knowledge of the model building type and seismic design level, and an estimate of earthquake demand, and (3) guidance for expert users, including estimation of damage to high potential loss (HPL) facilities.

Special buildings and their damage functions are described in Sections 6.2 through 6.5. Evaluation of damage to essential facilities is given in Section 6.6 and guidance for expert users is given in Section 6.7. Typically, sections of Chapter 6 reference (rather than repeat) material of the corresponding section of Chapter 5.

6.1.2 Essential Facility Classification

Facilities that provide services to the community and those that should be functional following an earthquake are considered to be essential facilities. Examples of essential facilities include hospitals, police stations, fire stations, emergency operations centers (EOC's) and schools. The methodology adopted for damage assessment of such facilities is explained in this section.

Essential facilities are classified on the basis of facility function and, in the case of hospitals, size. Table 6.1 lists the classes of essential facilities used in the Methodology. Hospitals are classified on the basis of number of beds, since the structural and nonstructural systems of a hospital are related to the size of the hospital (i.e., to the number of beds it contains).



Flowchart 6.1: Essential and High Potential Loss Facility Component Relationship to other Components in the Methodology

Table 6.1 Classification of Essential Facilities

No.	Label	Occupancy Class	Description
		Medical Care Facilities	
1	EFHS	Small Hospital	Hospital with less than 50 Beds
2	EFHM	Medium Hospital	Hospital with beds between 50 & 150
3	EFHL	Large Hospital	Hospital with greater than 150 Beds
4	EFMC	Medical Clinics	Clinics, Labs, Blood Banks
		Emergency Response	
5	EFFS	Fire Station	
6	EFPS	Police Station	
7	EFEO	Emergency Operation Centers	
		Schools	
8	EFS1	Schools	Primary/ Secondary Schools (K-12)
9	EFS2	Colleges/Universities	Community and State Colleges, State and Private Universities

It is the responsibility of the user to identify each essential facility as either a Code building or a Special building of a particular model building type and seismic design level. This chapter provides building damage functions for Special buildings that have significantly better than average seismic capacity. Chapter 5 provides building damage functions for Code-buildings. If the user is not able to determine that the essential facility is significantly better than average, then the facility should be modeled using Code building damage functions (i.e., the same methods as those developed in Chapter 5 for general building stock).

6.1.3 Input Requirements and Output Information

Input required to estimate essential facility damage using fragility and capacity curves includes the following two items:

- model building type (including height) and seismic design level that represents the essential facility (or type of essential facilities) of interest, and

- response spectrum (or PGA, for lifeline buildings, and PGD for ground failure evaluation) at the essential facility's site.

The response spectrum, PGA and PGD at the essential facility site are PESH outputs, described in Chapter 4.

The "output" of fragility curves is an estimate of the cumulative probability of being in or exceeding, each damage state for the given level of ground shaking (or ground failure). Cumulative damage probabilities are differenced to create discrete damage state probabilities, as described in Chapter 5 (Section 5.6). Discrete probabilities of damage are used directly as inputs to induced physical damage and direct economic and social loss modules, as shown in Flowchart 6.1.

Typically, the model building type (including height) is not known for each essential facility and must be inferred from the inventory of essential facilities using the occupancy/building type relationships described in Chapter 3. In general, performance of essential facilities is not expected to be better than the typical building of the representative model building type. Exceptions to this generalization include California hospitals of recent (post-1973) construction.

6.1.4 Form of Damage Functions

Building damage functions for essential facilities are of the same form as those described in Chapter 5 for general building stock. For each damage state, a lognormal fragility curve relates the probability of damage to PGA, PGD or spectral demand determined by the intersection of the model building type's capacity curve and the demand spectrum. Figure 6.1 provides an example of fragility curves for four damage states: Slight, Moderate, Extensive and Complete.

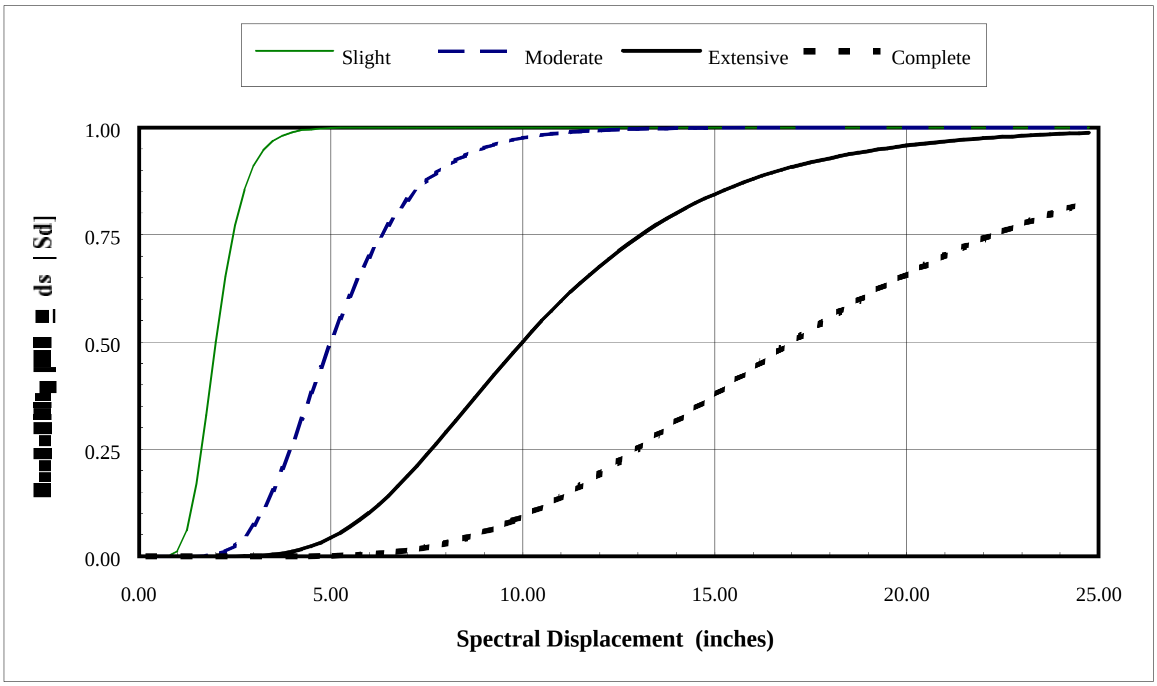


Figure 6.1 Example Fragility Curves for Slight, Moderate, Extensive and Complete Damage.

The fragility curves are driven by a PESH parameter. For ground failure, the PESH parameter used to drive fragility curves is permanent ground displacement (PGD). For ground shaking, the PESH parameter used to drive building fragility curves is peak spectral response (either displacement or acceleration), or peak ground acceleration (PGA) for essential lifeline facilities. Peak spectral response varies significantly for buildings that have different response properties and, therefore, requires knowledge of these properties.

Building response is characterized by building capacity curves. These curves describe the push-over displacement of each building type and seismic design level as a function of laterally-applied earthquake load. Design-, yield- and ultimate-capacity points define the shape of each building capacity curve. The Methodology estimates peak building response as the intersection of the building capacity curve and the demand spectrum at the building's location.

The demand spectrum is the 5%-damped PESH input spectrum reduced for higher levels of effective damping (e.g., effective damping includes both elastic damping and hysteretic damping associated with post-yield cyclic response of the building). Figure 6.2 illustrates the intersection of a typical building capacity curve and a typical demand spectrum (reduced for effective damping greater than 5% of critical).

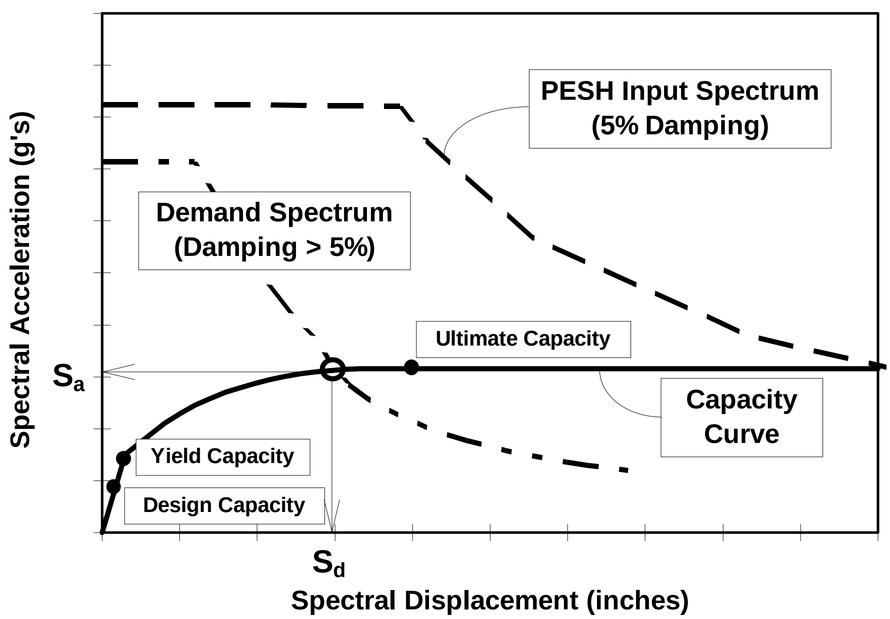


Figure 6.2 Example Building Capacity Curve and Demand Spectrum.

6.2 Description of Model Building Types

The model building types used for essential facilities are identical to those used for general building stock. These building types are described in Section 5.2 and listed in Table 5.1. Typical nonstructural components of essential facilities include those architectural, mechanical and electrical, and contents listed in Table 5.2 for general building stock.

Essential facilities also include certain special equipment, such as emergency generators, and certain special contents, such as those used to operate a hospital. Special equipment and contents of essential facilities are considered to be acceleration-sensitive nonstructural components of these facilities.

6.3 Description of Building Damage States

Building damage states for structural and nonstructural components of essential facilities are the same as those described in Section 5.3 for general building stock.

6.4 Building Damage Due to Ground Shaking - Special Buildings

6.4.1 Overview

This section describes capacity and fragility curves used in the Methodology to estimate the probability of Slight, Moderate, Extensive and Complete damage to Special buildings of a given model building type designed to High-, Moderate-, or Low-Code seismic standards. Special building damage functions are appropriate for evaluation of essential facilities when the user anticipates above-Code seismic performance for these facilities.

Capacity curves and fragility curves for Special buildings of High-Code, Moderate-Code, or Low-Code seismic design are based on modern code (e.g., 1976 *Uniform Building Code*, 1996 *NEHRP Provisions*, or later editions of these model codes) design criteria for various seismic design zones, as shown in Table 6.2. Additional description of seismic design levels may be found in Section 6.7.

Table 6.2 Approximate Basis for Seismic Design Levels

Seismic Design Level (I = 1.5)	Seismic Zone (1994 *Uniform Building Code*)	Map Area (1994 *NEHRP Provisions*)
High-Code	4	7
Moderate-Code	2B	5
Low-Code	1	3

The capacity and fragility curves represent buildings designed and constructed to modern seismic code provisions (e.g.,1994 *UBC*) using an importance factor of I = 1.5. Moderate-Code and Low-Code seismic design levels are included for completeness. Most essential facilities located in Seismic Zones O, T, 2A or 2B have not been designed for Special building code criteria.

6.4.2 Capacity Curves - Special Buildings

The building capacity curves for Special buildings are similar to those for the general building stock (Chapter 5), but with increased strength. Each curve is described by three control points that define model building capacity:

- Design Capacity
- Yield Capacity
- Ultimate Capacity

Design capacity represents the nominal building strength required by current model seismic code provisions (e.g., 1994 *UBC*) including an importance factor of $I = 1.5$. Wind design is not considered in the estimation of design capacity and certain buildings (e.g., taller buildings located in zones of low or moderate seismicity) may have a lateral design strength considerably greater than based on seismic code provisions.

Yield capacity represents the true lateral strength of the building considering redundancies in design, conservatism in code requirements and true (rather than nominal) strength of materials. Ultimate capacity represents the maximum strength of the building when the global structural system has reached a fully plastic state. An example building capacity curve is shown in Figure 6-3.

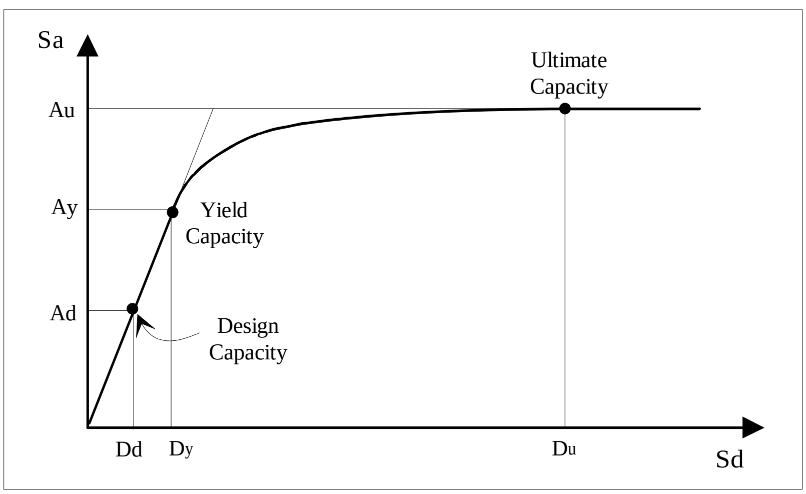


Figure 6.3 Example Building Capacity Curve.

The building capacity curves for Special buildings are constructed based on the same engineering properties (i.e., C_s, T_e, α_1, α_2, γ, λ, μ) as those used to describe capacity curves of Code buildings (i.e., Tables 5.4, 5.5 and 5.6), except for design strength, C_s, and ductility (μ). The design strength, C_s, is approximately based on the lateral-force design requirements of current seismic codes (e.g., 1994 *NEHRP* or 1994 *UBC*) using an importance factor of $I = 1.5$. Values of the "ductility" factor, μ, for Special buildings are based on Code-building ductility increased by 1.33 for Moderate-Code buildings and by 1.2 for Low-Code buildings. The ductility parameter defines the displacement value of capacity curve at the point where the curve reaches a fully plastic state.

Building capacity curves are assumed to have a range of possible properties that are lognormally distributed as a function of the ultimate strength (A_u) of each capacity curve. Special building capacity curves represent median estimates of building capacity. The variability of the capacity of each building type is assumed to be: $\beta(A_u) = 0.15$ for Special buildings. An example construction of median, 84th percentile (+1β) and 16th percentile (–1β) building capacity curves for a typical building is illustrated in Figure 6.4. Median capacity curves are intersected with demand spectra to estimate peak building response. The variability of the capacity curves is used, with other sources of variability and uncertainty, to define total fragility curve variability.

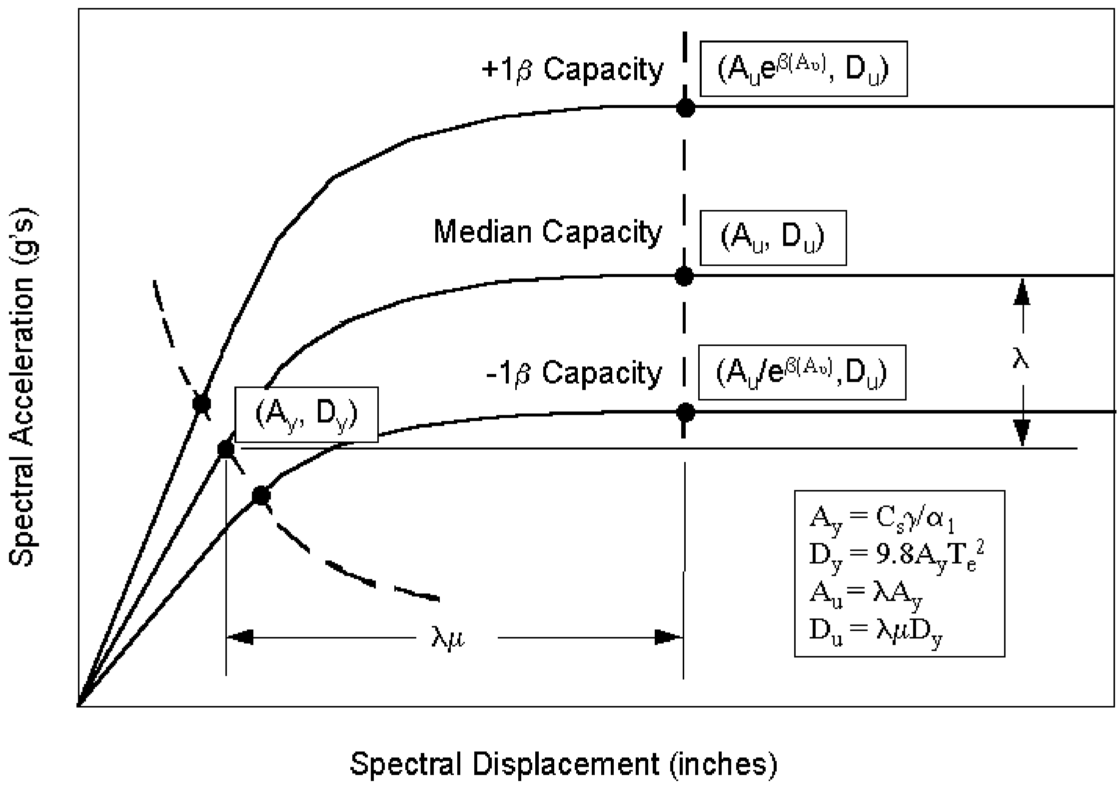


Figure 6.4 Example Construction of Median, +1β and -1β Building Capacity Curves.

Tables 6.3a, 6.3b and 6.3c summarize yield capacity and ultimate capacity control points for Special buildings of High-Code, Moderate-Code and Low-Code seismic design levels, respectively. Note that for the following tables, shaded boxes indicate types that are not permitted by current seismic codes.

Table 6.3a Special Building Capacity Curves - High-Code Seismic Design Level

Building Type	Yield Capacity Point		Ultimate Capacity Point	
	D_y (in.)	A_y (g)	D_u (in.)	A_u (g)
W1	0.72	0.600	17.27	1.800
W2	0.94	0.600	18.79	1.500
S1L	0.92	0.375	22.00	1.124
S1M	2.66	0.234	42.60	0.702
S1H	6.99	0.147	83.83	0.440
S2L	0.94	0.600	15.03	1.200
S2M	3.64	0.500	38.82	1.000
S2H	11.62	0.381	92.95	0.762
S3	0.94	0.600	15.03	1.200
S4L	0.58	0.480	10.36	1.080
S4M	1.64	0.400	19.65	0.900
S4H	5.23	0.305	47.05	0.685
S5L				
S5M				
S5H				
C1L	0.59	0.375	14.08	1.124
C1M	1.73	0.312	27.65	0.937
C1H	3.02	0.147	36.20	0.440
C2L	0.72	0.600	14.39	1.500
C2M	1.56	0.500	20.76	1.250
C2H	4.41	0.381	44.09	0.952
C3L				
C3M				
C3H				
PC1	1.08	0.900	17.27	1.800
PC2L	0.72	0.600	11.51	1.200
PC2M	1.56	0.500	16.61	1.000
PC2H	4.41	0.381	35.27	0.762
RM1L	0.96	0.800	15.34	1.600
RM1M	2.08	0.667	22.14	1.333
RM2L	0.96	0.800	15.34	1.600
RM2M	2.08	0.667	22.14	1.333
RM2H	5.88	0.508	47.02	1.015
URML				
URMM				
MH	0.27	0.225	4.32	0.450

Table 6.3b Special Building Capacity Curves - Moderate-Code Seismic Design Level

Building Type	Yield Capacity Point		Ultimate Capacity Point	
	D_y (in.)	A_y (g)	D_u (in.)	A_u (g)
W1	0.54	0.450	12.95	1.350
W2	0.47	0.300	9.40	0.750
S1L	0.46	0.187	11.00	0.562
S1M	1.33	0.117	21.30	0.351
S1H	3.49	0.073	41.91	0.220
S2L	0.47	0.300	7.52	0.600
S2M	1.82	0.250	19.41	0.500
S2H	5.81	0.190	46.47	0.381
S3	0.47	0.300	7.52	0.600
S4L	0.29	0.240	5.18	0.540
S4M	0.82	0.200	9.83	0.450
S4H	2.61	0.152	23.53	0.343
S5L				
S5M				
S5H				
C1L	0.29	0.187	7.04	0.562
C1M	0.86	0.156	13.83	0.468
C1H	1.51	0.073	18.10	0.220
C2L	0.36	0.300	7.19	0.750
C2M	0.78	0.250	10.38	0.625
C2H	2.21	0.190	22.05	0.476
C3L				
C3M				
C3H				
PC1	0.54	0.450	8.63	0.900
PC2L	0.36	0.300	5.76	0.600
PC2M	0.78	0.250	8.31	0.500
PC2H	2.21	0.190	17.64	0.381
RM1L	0.48	0.400	7.67	0.800
RM1M	1.04	0.333	11.07	0.667
RM2L	0.48	0.400	7.67	0.800
RM2M	1.04	0.333	11.07	0.667
RM2H	2.94	0.254	23.51	0.508
URML				
URMM				
MH	0.27	0.225	4.32	0.450

Table 6.3c Special Building Capacity Curves - Low-Code Seismic Design Level

Building Type	Yield Capacity Point		Ultimate Capacity Point	
	D_y (in.)	A_y (g)	D_u (in.)	A_u (g)
W1	0.36	0.300	6.48	0.900
W2	0.24	0.150	3.52	0.375
S1L	0.23	0.094	4.13	0.281
S1M	0.67	0.059	7.99	0.176
S1H	1.75	0.037	15.72	0.110
S2L	0.24	0.150	2.82	0.300
S2M	0.91	0.125	7.28	0.250
S2H	2.91	0.095	17.43	0.190
S3	0.24	0.150	2.82	0.300
S4L	0.14	0.120	1.94	0.270
S4M	0.41	0.100	3.69	0.225
S4H	1.31	0.076	8.82	0.171
S5L	0.18	0.150	2.16	0.300
S5M	0.51	0.125	4.09	0.250
S5H	1.63	0.095	9.80	0.190
C1L	0.15	0.094	2.64	0.281
C1M	0.43	0.078	5.19	0.234
C1H	0.75	0.037	6.79	0.110
C2L	0.18	0.150	2.70	0.375
C2M	0.39	0.125	3.89	0.313
C2H	1.10	0.095	8.27	0.238
C3L	0.18	0.150	2.43	0.338
C3M	0.39	0.125	3.50	0.281
C3H	1.10	0.095	7.44	0.214
PC1	0.27	0.225	3.24	0.450
PC2L	0.18	0.150	2.16	0.300
PC2M	0.39	0.125	3.11	0.250
PC2H	1.10	0.095	6.61	0.190
RM1L	0.24	0.200	2.88	0.400
RM1M	0.52	0.167	4.15	0.333
RM2L	0.24	0.200	2.88	0.400
RM2M	0.52	0.167	4.15	0.333
RM2H	1.47	0.127	8.82	0.254
URML	0.36	0.300	4.32	0.600
URMM	0.41	0.167	3.26	0.333
MH	0.27	0.225	4.32	0.450

6.4.3 Fragility Curves - Special Buildings

This section describes Special building fragility curves for Slight, Moderate, Extensive and Complete structural damage states and Slight, Moderate, Extensive and Complete nonstructural damage states. Each fragility curve is characterized by a median and a lognormal standard deviation (β) value of PESH demand. Spectral displacement is the PESH parameter used for structural damage and nonstructural damage to drift-sensitive components. Spectral acceleration is the PESH parameter used for nonstructural damage to acceleration-sensitive components.

Special building fragility curves for ground failure are the same as those of Code buildings (Section 5.5).

6.4.3.1 Background

The form of the fragility curves for Special buildings is the same as that used for Code buildings. The probability of being in, or exceeding, a given damage state is modeled as a cumulative lognormal distribution. Given the appropriate PESH parameter (e.g., spectral displacement, S_d, for structural damage), the probability of being in or exceeding a damage state, ds, is modeled as follows:

$$P\left[ds \middle| S_d\right] = \Phi\left[\frac{1}{\beta_{ds}} \ln\left(\frac{S_d}{\bar{S}_{d,ds}}\right)\right] \tag{6-1}$$

where: $\bar{S}_{d,ds}$ is the median value of spectral displacement at which the building reaches the threshold of the damage state, ds,

β_{ds} is the standard deviation of the natural logarithm of spectral displacement of damage state, ds, and

Φ is the standard normal cumulative distribution function.

6.4.3.2 Structural Damage - Special Buildings

Structural damage states for Special buildings are based on drift ratios that are assumed to be slightly higher than those of Code buildings of the same model building type and seismic design level. It is difficult to quantify this improvement in displacement capacity since it is a function not just of building type and design parameters, but also design review and construction inspection. It is assumed that the improvement in displacement capacity results in a 1.25 increase in drift capacity of each damage state for all Special building types and seismic design levels. Special buildings perform better than Code buildings due to increased structure strength (of the capacity curves) and increased displacement capacity (of the fragility curves). In general, increased strength tends to most improve building performance near yield and improved displacement capacity tends to most improve the ultimate capacity of the building.

Median values of Special building structural fragility are based on drift ratios (that describe the threshold of damage states and the height of the building to point of push-over mode displacement using the same approach as that of Code buildings (Section 5.4.3.2).

The variability of Special building structural damage is based on the same approach as that of Code buildings (Section 5.4.3.3). The total variability of each structural damage state, β_{Sds}, is modeled by the combination of following three contributors to damage variability:

- uncertainty in the damage state threshold of the structural system ($\beta_{M(Sds)}$ = 0.4, for all structural damage states and building types)

- variability in capacity (response) properties of the model building type/seismic design level of interest ($\beta_{C(Au)}$ = 0.15 for Special buildings), and

- variability in response due to the spatial variability of ground motion demand ($\beta_{D(A)}$ = 0.45 and $\beta_{C(V)}$ = 0.50).is based on the dispersion factor typical of the attenuation of large-magnitude earthquakes as in the WUS (Chapter 4).

Each of these three contributors to damage state variability are assumed to be lognormally distributed random variables. Capacity and demand are dependent parameters and a convolution process is used to derive combined capacity/demand variability of each structural damage state. Capacity/demand variability is then combined with damage state uncertainty, as described in Section 5.4.3.3.

Tables 6.4a, 6.4b and 6.4c summarize median and lognormal standard deviation (β_{Sds}) values for Slight, Moderate, Extensive and Complete structural damage states of Special buildings for High-Code, Moderate-Code and Low-Code seismic design levels, respectively. Note that for the following tables, shaded boxes indicate types that are not permitted by current seismic codes.

Table 6.4a Building Structural Fragility - High-Code Seismic Design Level

Building Properties			Interstory Drift at Threshold of Damage State				Spectral Displacement (inches)							
Type	Height (inches)						Slight		Moderate		Extensive		Complete	
	Roof	Modal	Slight	Moderate	Extensive	Complete	Median	Beta	Median	Beta	Median	Beta	Median	Beta
W1	168	126	0.0050	0.0150	0.0500	0.1250	0.63	0.66	1.89	0.72	6.30	0.72	15.75	0.91
W2	288	216	0.0050	0.0150	0.0500	0.1250	1.08	0.69	3.24	0.77	10.80	0.89	27.00	0.85
S1L	288	216	0.0075	0.0150	0.0375	0.1000	1.62	0.67	3.24	0.70	8.10	0.71	21.60	0.68
S1M	720	540	0.0050	0.0100	0.0250	0.0667	2.70	0.62	5.40	0.62	13.50	0.63	36.00	0.71
S1H	1872	1123	0.0037	0.0075	0.0188	0.0500	4.21	0.63	8.42	0.62	21.06	0.62	56.16	0.63
S2L	288	216	0.0063	0.0125	0.0375	0.1000	1.35	0.69	2.70	0.80	8.10	0.89	21.60	0.84
S2M	720	540	0.0042	0.0083	0.0250	0.0667	2.25	0.62	4.50	0.66	13.50	0.66	36.00	0.71
S2H	1872	1123	0.0031	0.0063	0.0188	0.0500	3.51	0.62	7.02	0.63	21.06	0.63	56.16	0.66
S3	180	135	0.0050	0.0100	0.0300	0.0875	0.68	0.66	1.35	0.71	4.05	0.80	11.81	0.90
S4L	288	216	0.0050	0.0100	0.0300	0.0875	1.08	0.77	2.16	0.82	6.48	0.92	18.90	0.91
S4M	720	540	0.0033	0.0067	0.0200	0.0583	1.80	0.69	3.60	0.67	10.80	0.68	31.50	0.82
S4H	1872	1123	0.0025	0.0050	0.0150	0.0438	2.81	0.62	5.62	0.63	16.85	0.65	49.14	0.73
S5L														
S5M														
S5H														
C1L	240	180	0.0063	0.0125	0.0375	0.1000	1.13	0.69	2.25	0.74	6.75	0.82	18.00	0.81
C1M	600	450	0.0042	0.0083	0.0250	0.0667	1.87	0.63	3.75	0.65	11.25	0.66	30.00	0.71
C1H	1440	864	0.0031	0.0063	0.0188	0.0500	2.70	0.63	5.40	0.63	16.20	0.63	43.20	0.69
C2L	240	180	0.0050	0.0125	0.0375	0.1000	0.90	0.69	2.25	0.72	6.75	0.82	18.00	0.95
C2M	600	450	0.0033	0.0083	0.0250	0.0667	1.50	0.65	3.75	0.69	11.25	0.66	30.00	0.70
C2H	1440	864	0.0025	0.0063	0.0188	0.0500	2.16	0.62	5.40	0.63	16.20	0.64	43.20	0.69
C3L														
C3M														
C3H														
PC1	180	135	0.0050	0.0100	0.0300	0.0875	0.68	0.63	1.35	0.74	4.05	0.79	11.81	0.96
PC2L	240	180	0.0050	0.0100	0.0300	0.0875	0.90	0.76	1.80	0.80	5.40	0.87	15.75	0.97
PC2M	600	450	0.0033	0.0067	0.0200	0.0583	1.50	0.66	3.00	0.73	9.00	0.72	26.25	0.73
PC2H	1440	864	0.0025	0.0050	0.0150	0.0438	2.16	0.62	4.32	0.64	12.96	0.65	37.80	0.74
RM1L	240	180	0.0050	0.0100	0.0300	0.0875	0.90	0.70	1.80	0.74	5.40	0.76	15.75	0.98
RM1M	600	450	0.0033	0.0067	0.0200	0.0583	1.50	0.63	3.00	0.68	9.00	0.70	26.25	0.70
RM2L	240	180	0.0050	0.0100	0.0300	0.0875	0.90	0.66	1.80	0.70	5.40	0.76	15.75	0.97
RM2M	600	450	0.0033	0.0067	0.0200	0.0583	1.50	0.63	3.00	0.70	9.00	0.69	26.25	0.68
RM2H	1440	864	0.0025	0.0050	0.0150	0.0438	2.16	0.63	4.32	0.63	12.96	0.63	37.80	0.65
URML														
URMM														
MH	120	120	0.0050	0.0100	0.0300	0.0875	0.60	0.81	1.20	0.89	3.60	0.97	10.50	0.86

Table 6.4b Building Structural Fragility - Moderate-Code Seismic Design Level

Building Properties			Interstory Drift at Threshold of Damage State				Spectral Displacement (inches)							
Type	Height (inches)						Slight		Moderate		Extensive		Complete	
	Roof	Modal	Slight	Moderate	Extensive	Complete	Median	Beta	Median	Beta	Median	Beta	Median	Beta
W1	168	126	0.0050	0.0124	0.0383	0.0937	0.63	0.76	1.56	0.77	4.82	0.78	11.81	0.96
W2	288	216	0.0050	0.0124	0.0383	0.0938	1.08	0.79	2.68	0.86	8.27	0.88	20.25	0.84
S1L	288	216	0.0075	0.0130	0.0294	0.0750	1.62	0.73	2.80	0.71	6.35	0.70	16.20	0.77
S1M	720	540	0.0050	0.0086	0.0196	0.0500	2.70	0.64	4.67	0.65	10.58	0.66	27.00	0.75
S1H	1872	1123	0.0037	0.0065	0.0147	0.0375	4.21	0.62	7.29	0.62	16.51	0.66	42.12	0.70
S2L	288	216	0.0063	0.0108	0.0292	0.0750	1.35	0.82	2.34	0.85	6.30	0.89	16.20	0.85
S2M	720	540	0.0042	0.0072	0.0194	0.0500	2.25	0.66	3.90	0.66	10.50	0.68	27.00	0.81
S2H	1872	1123	0.0031	0.0054	0.0146	0.0375	3.51	0.62	6.08	0.63	16.38	0.65	42.12	0.71
S3	180	135	0.0050	0.0087	0.0234	0.0656	0.68	0.77	1.17	0.81	3.16	0.89	8.86	0.89
S4L	288	216	0.0050	0.0087	0.0234	0.0656	1.08	0.88	1.87	0.92	5.05	0.98	14.18	0.87
S4M	720	540	0.0033	0.0058	0.0156	0.0437	1.80	0.70	3.12	0.67	8.41	0.70	23.62	0.90
S4H	1872	1123	0.0025	0.0043	0.0117	0.0328	2.81	0.66	4.87	0.66	13.13	0.70	36.86	0.81
S5L														
S5M														
S5H														
C1L	240	180	0.0063	0.0108	0.0292	0.0750	1.13	0.80	1.95	0.82	5.25	0.84	13.50	0.81
C1M	600	450	0.0042	0.0072	0.0194	0.0500	1.87	0.66	3.25	0.67	8.75	0.66	22.50	0.84
C1H	1440	864	0.0031	0.0054	0.0146	0.0375	2.70	0.64	4.68	0.64	12.60	0.68	32.40	0.81
C2L	240	180	0.0050	0.0105	0.0289	0.0750	0.90	0.77	1.89	0.86	5.21	0.91	13.50	0.89
C2M	600	450	0.0033	0.0070	0.0193	0.0500	1.50	0.71	3.16	0.70	8.68	0.69	22.50	0.83
C2H	1440	864	0.0025	0.0053	0.0145	0.0375	2.16	0.64	4.55	0.65	12.51	0.66	32.40	0.79
C3L														
C3M														
C3H														
PC1	180	135	0.0050	0.0087	0.0234	0.0656	0.68	0.79	1.17	0.81	3.16	0.86	8.86	1.00
PC2L	240	180	0.0050	0.0087	0.0234	0.0656	0.90	0.83	1.56	0.89	4.21	0.97	11.81	0.89
PC2M	600	450	0.0033	0.0058	0.0156	0.0438	1.50	0.76	2.60	0.74	7.01	0.73	19.69	0.88
PC2H	1440	864	0.0025	0.0043	0.0117	0.0328	2.16	0.65	3.75	0.66	10.10	0.70	28.35	0.81
RM1L	240	180	0.0050	0.0087	0.0234	0.0656	0.90	0.80	1.56	0.85	4.21	0.92	11.81	0.97
RM1M	600	450	0.0033	0.0058	0.0156	0.0438	1.50	0.73	2.60	0.75	7.01	0.75	19.69	0.80
RM2L	240	180	0.0050	0.0087	0.0234	0.0656	0.90	0.77	1.56	0.81	4.21	0.92	11.81	0.96
RM2M	600	450	0.0033	0.0058	0.0156	0.0438	1.50	0.72	2.60	0.72	7.01	0.72	19.69	0.77
RM2H	1440	864	0.0025	0.0043	0.0117	0.0328	2.16	0.63	3.75	0.65	10.10	0.66	28.35	0.76
URML														
URMM														
MH	120	120	0.0050	0.0100	0.0300	0.0875	0.60	0.81	1.20	0.89	3.60	0.97	10.50	0.86

Table 6.4c Special Building Structural Fragility - Low-Code Seismic Design Level

Building Properties			Interstory Drift at Threshold of Damage State				Spectral Displacement (inches)							
Type	Height (inches)						Slight		Moderate		Extensive		Complete	
	Roof	Modal	Slight	Moderate	Extensive	Complete	Median	Beta	Median	Beta	Median	Beta	Median	Beta
W1	168	126	0.0050	0.0124	0.0383	0.0937	0.63	0.80	1.56	0.81	4.82	0.88	11.81	1.01
W2	288	216	0.0050	0.0124	0.0383	0.0938	1.08	0.89	2.68	0.89	8.27	0.86	20.25	0.97
S1L	288	216	0.0075	0.0119	0.0253	0.0625	1.62	0.73	2.58	0.73	5.47	0.75	13.50	0.93
S1M	720	540	0.0050	0.0080	0.0169	0.0417	2.70	0.66	4.30	0.70	9.12	0.78	22.50	0.91
S1H	1872	1123	0.0037	0.0060	0.0127	0.0313	4.21	0.64	6.72	0.66	14.23	0.68	35.10	0.86
S2L	288	216	0.0063	0.0100	0.0250	0.0625	1.35	0.89	2.16	0.89	5.40	0.88	13.50	0.97
S2M	720	540	0.0042	0.0067	0.0167	0.0417	2.25	0.67	3.60	0.68	9.00	0.74	22.50	0.92
S2H	1872	1123	0.0031	0.0050	0.0125	0.0313	3.51	0.62	5.62	0.63	14.04	0.68	35.10	0.84
S3	180	135	0.0050	0.0080	0.0201	0.0547	0.68	0.89	1.08	0.90	2.71	0.98	7.38	0.85
S4L	288	216	0.0050	0.0080	0.0200	0.0547	1.08	0.98	1.73	0.95	4.33	0.97	11.81	0.98
S4M	720	540	0.0033	0.0053	0.0134	0.0364	1.80	0.69	2.88	0.72	7.22	0.81	19.68	0.98
S4H	1872	1123	0.0025	0.0040	0.0100	0.0273	2.81	0.66	4.50	0.67	11.26	0.78	30.71	0.93
S5L	288	216	0.0038	0.0075	0.0188	0.0438	0.81	1.00	1.62	1.00	4.05	1.03	9.45	0.91
S5M	720	540	0.0025	0.0050	0.0125	0.0292	1.35	0.74	2.70	0.72	6.75	0.78	15.75	0.94
S5H	1872	1123	0.0019	0.0037	0.0094	0.0219	2.11	0.67	4.21	0.69	10.53	0.74	24.57	0.90
C1L	240	180	0.0063	0.0100	0.0250	0.0625	1.13	0.85	1.80	0.85	4.50	0.88	11.25	0.95
C1M	600	450	0.0042	0.0067	0.0167	0.0417	1.87	0.70	3.00	0.69	7.50	0.75	18.75	0.95
C1H	1440	864	0.0031	0.0050	0.0125	0.0313	2.70	0.66	4.32	0.71	10.80	0.79	27.00	0.95
C2L	240	180	0.0050	0.0096	0.0247	0.0625	0.90	0.91	1.72	0.94	4.44	1.01	11.25	0.90
C2M	600	450	0.0033	0.0064	0.0164	0.0417	1.50	0.76	2.86	0.74	7.40	0.74	18.75	0.94
C2H	1440	864	0.0025	0.0048	0.0123	0.0313	2.16	0.66	4.12	0.67	10.66	0.74	27.00	0.91
C3L	240	180	0.0038	0.0075	0.0188	0.0438	0.68	0.92	1.35	0.99	3.38	1.04	7.88	0.88
C3M	600	450	0.0025	0.0050	0.0125	0.0292	1.12	0.77	2.25	0.79	5.62	0.78	13.12	0.93
C3H	1440	864	0.0019	0.0038	0.0094	0.0219	1.62	0.68	3.24	0.69	8.10	0.70	18.90	0.88
PC1	180	135	0.0050	0.0080	0.0201	0.0547	0.68	0.89	1.08	0.95	2.71	1.00	7.38	0.96
PC2L	240	180	0.0050	0.0080	0.0201	0.0547	0.90	0.98	1.44	0.98	3.61	1.02	9.84	0.91
PC2M	600	450	0.0033	0.0053	0.0134	0.0364	1.50	0.76	2.40	0.75	6.02	0.75	16.40	0.94
PC2H	1440	864	0.0025	0.0040	0.0100	0.0273	2.16	0.66	3.46	0.68	8.66	0.73	23.63	0.92
RM1L	240	180	0.0050	0.0080	0.0201	0.0547	0.90	0.97	1.44	1.01	3.61	1.07	9.84	0.88
RM1M	600	450	0.0033	0.0053	0.0134	0.0364	1.50	0.78	2.40	0.78	6.02	0.78	16.40	0.94
RM2L	240	180	0.0050	0.0080	0.0201	0.0547	0.90	0.94	1.44	0.98	3.61	1.05	9.84	0.89
RM2M	600	450	0.0033	0.0053	0.0134	0.0364	1.50	0.76	2.40	0.75	6.02	0.75	16.40	0.92
RM2H	1440	864	0.0025	0.0040	0.0100	0.0273	2.16	0.66	3.46	0.67	8.66	0.80	23.63	0.89
URML	180	135	0.0038	0.0075	0.0187	0.0438	0.51	0.89	1.01	0.91	2.53	0.96	5.91	1.09
URMM	420	315	0.0025	0.0050	0.0125	0.0292	0.79	0.81	1.57	0.84	3.94	0.87	9.19	0.82
MH	120	120	0.0050	0.0100	0.0300	0.0875	0.60	0.81	1.20	0.89	3.60	0.97	10.50	0.86

6.4.3.3 Nonstructural Damage - Drift-Sensitive

Damage states of nonstructural drift-sensitive components of Special buildings are based on the same drift ratios as those of Code buildings (Table 5.10). Even for essential facilities, nonstructural components are typically not designed or detailed for special earthquake displacements. Improvement in the performance of drift-sensitive components of Special buildings is assumed to be entirely a function of drift reduction due to the increased stiffness and strength of the structures of these buildings.

Median values of drift-sensitive nonstructural fragility curves are based on global building displacement (in inches), calculated as the product of: (1) drift ratio, (2) building height and (3) the fraction of building height at the location of push-over mode displacement (α_2).

The total variability of each nonstructural drift-sensitive damage state, β_{NSDds}, is modeled by the combination of following three contributors to damage variability:

- uncertainty in the damage state threshold of nonstructural components ($\beta_{M(NSDds)}$ = 0.5, for all structural damage states and building types,

- variability in capacity (response) properties of the model building type that contains the nonstructural components of interest ($\beta_{C(Au)}$ = 0.15 for Special buildings, and

- variability in response of the model building type due to the spatial variability of ground motion demand ($\beta_{D(A)}$ = 0.45 and $\beta_{C(V)}$ = 0.50).

Each of these three contributors to damage state variability are assumed to be lognormally distributed random variables. Capacity and demand are dependent parameters and a convolution process is used to derive combined capacity/demand variability of each nonstructural damage state. Capacity/demand variability is then combined with damage state uncertainty, as described in Section 5.4.3.3.

Tables 6.5a, 6.5b and 6.5c summarize median and lognormal standard deviation (β_{NSDds}) values for Slight, Moderate, Extensive and Complete damage states of nonstructural drift-sensitive components of Special buildings for High-Code, Moderate-Code and Low-Code seismic design levels, respectively. Note that for the following tables, shaded boxes indicate types that are not permitted by current seismic codes.

Table 6.5a Special Building Nonstructural Drift-Sensitive Fragility - High-Code Seismic Design Level

Building Type	Median Spectral Displacement (inches) and Logstandard Deviation (Beta)							
	Slight		Moderate		Extensive		Complete	
	Median	Beta	Median	Beta	Median	Beta	Median	Beta
W1	0.50	0.74	1.01	0.77	3.15	0.79	6.30	0.78
W2	0.86	0.76	1.73	0.77	5.40	0.88	10.80	0.93
S1L	0.86	0.72	1.73	0.76	5.40	0.75	10.80	0.74
S1M	2.16	0.68	4.32	0.68	13.50	0.70	27.00	0.73
S1H	4.49	0.70	8.99	0.69	28.08	0.69	56.16	0.70
S2L	0.86	0.74	1.73	0.77	5.40	0.90	10.80	0.95
S2M	2.16	0.70	4.32	0.72	13.50	0.73	27.00	0.72
S2H	4.49	0.71	8.99	0.69	28.08	0.70	56.16	0.73
S3	0.54	0.70	1.08	0.76	3.38	0.83	6.75	0.93
S4L	0.86	0.81	1.73	0.84	5.40	0.93	10.80	1.00
S4M	2.16	0.76	4.32	0.74	13.50	0.75	27.00	0.82
S4H	4.49	0.70	8.99	0.71	28.08	0.72	56.16	0.80
S5L								
S5M								
S5H								
C1L	0.72	0.77	1.44	0.76	4.50	0.84	9.00	0.88
C1M	1.80	0.71	3.60	0.71	11.25	0.72	22.50	0.71
C1H	3.46	0.70	6.91	0.69	21.60	0.71	43.20	0.75
C2L	0.72	0.76	1.44	0.76	4.50	0.80	9.00	0.94
C2M	1.80	0.74	3.60	0.76	11.25	0.73	22.50	0.74
C2H	3.46	0.69	6.91	0.69	21.60	0.71	43.20	0.75
C3L								
C3M								
C3H								
PC1	0.54	0.69	1.08	0.78	3.38	0.85	6.75	0.88
PC2L	0.72	0.80	1.44	0.83	4.50	0.90	9.00	1.03
PC2M	1.80	0.75	3.60	0.80	11.25	0.77	22.50	0.77
PC2H	3.46	0.70	6.91	0.71	21.60	0.73	43.20	0.82
RM1L	0.72	0.74	1.44	0.80	4.50	0.80	9.00	0.94
RM1M	1.80	0.70	3.60	0.77	11.25	0.77	22.50	0.77
RM2L	0.72	0.74	1.44	0.76	4.50	0.78	9.00	0.96
RM2M	1.80	0.71	3.60	0.78	11.25	0.74	22.50	0.74
RM2H	3.46	0.69	6.91	0.69	21.60	0.71	43.20	0.74
URML								
URMM								
MH	0.48	0.85	0.96	0.92	3.00	0.98	6.00	0.99

Table 6.5b Special Building Nonstructural Drift-Sensitive Fragility - Moderate-Code Seismic Design Level

Building Type	Median Spectral Displacement (inches) and Logstandard Deviation (Beta)							
	Slight		Moderate		Extensive		Complete	
	Median	Beta	Median	Beta	Median	Beta	Median	Beta
W1	0.50	0.77	1.01	0.82	3.15	0.84	6.30	0.87
W2	0.86	0.84	1.73	0.88	5.40	0.93	10.80	0.93
S1L	0.86	0.78	1.73	0.78	5.40	0.78	10.80	0.76
S1M	2.16	0.71	4.32	0.71	13.50	0.73	27.00	0.81
S1H	4.49	0.69	8.99	0.69	28.08	0.72	56.16	0.82
S2L	0.86	0.81	1.73	0.91	5.40	0.96	10.80	0.89
S2M	2.16	0.73	4.32	0.74	13.50	0.73	27.00	0.87
S2H	4.49	0.69	8.99	0.70	28.08	0.74	56.16	0.84
S3	0.54	0.82	1.08	0.86	3.38	0.97	6.75	0.95
S4L	0.86	0.89	1.73	0.97	5.40	1.02	10.80	0.94
S4M	2.16	0.76	4.32	0.74	13.50	0.84	27.00	0.97
S4H	4.49	0.71	8.99	0.73	28.08	0.83	56.16	0.94
S5L								
S5M								
S5H								
C1L	0.72	0.80	1.44	0.86	4.50	0.88	9.00	0.88
C1M	1.80	0.73	3.60	0.72	11.25	0.74	22.50	0.89
C1H	3.46	0.71	6.91	0.71	21.60	0.79	43.20	0.93
C2L	0.72	0.84	1.44	0.87	4.50	0.95	9.00	1.00
C2M	1.80	0.79	3.60	0.76	11.25	0.76	22.50	0.88
C2H	3.46	0.70	6.91	0.71	21.60	0.77	43.20	0.87
C3L								
C3M								
C3H								
PC1	0.54	0.82	1.08	0.87	3.38	0.93	6.75	1.02
PC2L	0.72	0.88	1.44	0.95	4.50	1.03	9.00	0.99
PC2M	1.80	0.84	3.60	0.77	11.25	0.79	22.50	0.95
PC2H	3.46	0.72	6.91	0.74	21.60	0.84	43.20	0.94
RM1L	0.72	0.86	1.44	0.88	4.50	0.99	9.00	1.04
RM1M	1.80	0.80	3.60	0.79	11.25	0.79	22.50	0.88
RM2L	0.72	0.81	1.44	0.86	4.50	0.97	9.00	1.03
RM2M	1.80	0.78	3.60	0.77	11.25	0.77	22.50	0.88
RM2H	3.46	0.71	6.91	0.71	21.60	0.74	43.20	0.87
URML								
URMM								
MH	0.48	0.85	0.96	0.92	3.00	0.98	6.00	0.99

Table 6.5c Special Building Nonstructural Drift-Sensitive Fragility - Low-Code Seismic Design Level

Building Type	Median Spectral Displacement (inches) and Logstandard Deviation (Beta)							
	Slight		Moderate		Extensive		Complete	
	Median	Beta	Median	Beta	Median	Beta	Median	Beta
W1	0.50	0.83	1.01	0.86	3.15	0.88	6.30	1.00
W2	0.86	0.93	1.73	0.94	5.40	0.99	10.80	0.93
S1L	0.86	0.81	1.73	0.80	5.40	0.80	10.80	0.94
S1M	2.16	0.73	4.32	0.76	13.50	0.86	27.00	0.98
S1H	4.49	0.71	8.99	0.74	28.08	0.87	56.16	0.98
S2L	0.86	0.94	1.73	0.93	5.40	0.93	10.80	0.98
S2M	2.16	0.73	4.32	0.76	13.50	0.91	27.00	0.99
S2H	4.49	0.71	8.99	0.74	28.08	0.85	56.16	0.96
S3	0.54	0.89	1.08	0.96	3.38	1.01	6.75	0.90
S4L	0.86	1.02	1.73	0.99	5.40	0.95	10.80	1.01
S4M	2.16	0.76	4.32	0.84	13.50	0.95	27.00	1.04
S4H	4.49	0.74	8.99	0.87	28.08	0.96	56.16	1.03
S5L	0.86	1.04	1.73	1.04	5.40	1.00	10.80	0.99
S5M	2.16	0.78	4.32	0.84	13.50	0.97	27.00	1.04
S5H	4.49	0.76	8.99	0.87	28.08	0.96	56.16	1.03
C1L	0.72	0.90	1.44	0.92	4.50	0.93	9.00	0.93
C1M	1.80	0.74	3.60	0.77	11.25	0.94	22.50	1.00
C1H	3.46	0.75	6.91	0.86	21.60	0.97	43.20	1.03
C2L	0.72	0.93	1.44	0.99	4.50	1.06	9.00	0.92
C2M	1.80	0.80	3.60	0.80	11.25	0.91	22.50	1.00
C2H	3.46	0.73	6.91	0.80	21.60	0.93	43.20	1.01
C3L	0.72	0.99	1.44	1.05	4.50	1.06	9.00	0.93
C3M	1.80	0.84	3.60	0.83	11.25	0.95	22.50	1.01
C3H	3.46	0.76	6.91	0.84	21.60	0.96	43.20	1.03
PC1	0.54	0.92	1.08	0.99	3.38	1.07	6.75	1.02
PC2L	0.72	0.99	1.44	1.02	4.50	1.02	9.00	0.95
PC2M	1.80	0.81	3.60	0.82	11.25	0.95	22.50	1.02
PC2H	3.46	0.74	6.91	0.86	21.60	0.96	43.20	1.02
RM1L	0.72	0.98	1.44	1.06	4.50	1.08	9.00	0.94
RM1M	1.80	0.83	3.60	0.84	11.25	0.91	22.50	0.99
RM2L	0.72	0.94	1.44	1.03	4.50	1.07	9.00	0.92
RM2M	1.80	0.81	3.60	0.80	11.25	0.91	22.50	0.99
RM2H	3.46	0.74	6.91	0.79	21.60	0.92	43.20	1.01
URML	0.54	0.93	1.08	0.98	3.38	1.05	6.75	1.11
URMM	1.26	0.89	2.52	0.88	7.88	0.87	15.75	0.99
MH	0.48	0.85	0.96	0.92	3.00	0.98	6.00	0.99

6.4.3.4 Nonstructural Damage - Acceleration-Sensitive Components

Damage states of nonstructural acceleration-sensitive components of Special buildings are based on the peak floor accelerations of Code buildings of seismic design level (Table 5.12) increased by a factor of 1.5. A factor of 1.5 on damage-state acceleration reflects increased anchorage strength of nonstructural acceleration-sensitive components of Special buildings.

The floor acceleration values are used directly as median values, assuming average upper-floor demand is represented by response at the point of the push-over mode displacement.

The total variability of each damage state, β_{NSAds}, is modeled by the combination of following three contributors to nonstructural acceleration-sensitive damage variability:

- uncertainty in the damage state threshold of nonstructural components ($\beta_{M(NSAds)}$ = 0.6, for all structural damage states and building types,

- variability in capacity (response) properties of the model building type that contains the nonstructural components of interest ($\beta_{C(Au)}$ = 0.15 for Special buildings, and

- variability in response of the model building type due to the spatial variability of ground motion demand ($\beta_{D(A)}$ = 0.45 and $\beta_{C(V)}$ = 0.50).

Each of these three contributors to damage state variability are assumed to be lognormally distributed random variables. Capacity and demand are dependent parameters and a convolution process is used to derive combined capacity/demand variability of each nonstructural damage state. Capacity/demand variability is then combined with damage state uncertainty, as described in Section 5.4.3.3.

Tables 6.6a, 6.6b and 6.6c summarize median and lognormal standard deviation (β_{NSAds}) values for Slight, Moderate, Extensive and Complete damage states of nonstructural acceleration-sensitive components of Special buildings for High-Code, Moderate-Code and Low-Code seismic design levels, respectively.

Table 6.6a Special Building Nonstructural Acceleration-Sensitive Fragility - High-Code Seismic Design Level

Building Type	Median Spectral Acceleration (g) and Logstandard Deviation (Beta)							
	Slight		Moderate		Extensive		Complete	
	Median	Beta	Median	Beta	Median	Beta	Median	Beta
W1	0.45	0.72	0.90	0.68	1.80	0.68	3.60	0.68
W2	0.45	0.69	0.90	0.67	1.80	0.68	3.60	0.68
S1L	0.45	0.66	0.90	0.67	1.80	0.67	3.60	0.67
S1M	0.45	0.66	0.90	0.67	1.80	0.68	3.60	0.68
S1H	0.45	0.67	0.90	0.66	1.80	0.66	3.60	0.66
S2L	0.45	0.66	0.90	0.67	1.80	0.66	3.60	0.66
S2M	0.45	0.68	0.90	0.65	1.80	0.65	3.60	0.65
S2H	0.45	0.67	0.90	0.65	1.80	0.65	3.60	0.65
S3	0.45	0.68	0.90	0.67	1.80	0.66	3.60	0.66
S4L	0.45	0.67	0.90	0.67	1.80	0.67	3.60	0.67
S4M	0.45	0.66	0.90	0.65	1.80	0.66	3.60	0.66
S4H	0.45	0.66	0.90	0.65	1.80	0.63	3.60	0.63
S5L								
S5M								
S5H								
C1L	0.45	0.67	0.90	0.68	1.80	0.67	3.60	0.67
C1M	0.45	0.66	0.90	0.66	1.80	0.66	3.60	0.66
C1H	0.45	0.67	0.90	0.65	1.80	0.65	3.60	0.65
C2L	0.45	0.68	0.90	0.67	1.80	0.67	3.60	0.63
C2M	0.45	0.68	0.90	0.65	1.80	0.64	3.60	0.64
C2H	0.45	0.68	0.90	0.65	1.80	0.64	3.60	0.64
C3L								
C3M								
C3H								
PC1	0.45	0.72	0.90	0.66	1.80	0.67	3.60	0.63
PC2L	0.45	0.68	0.90	0.67	1.80	0.66	3.60	0.66
PC2M	0.45	0.67	0.90	0.64	1.80	0.65	3.60	0.65
PC2H	0.45	0.66	0.90	0.64	1.80	0.63	3.60	0.63
RM1L	0.45	0.73	0.90	0.66	1.80	0.68	3.60	0.64
RM1M	0.45	0.69	0.90	0.65	1.80	0.64	3.60	0.64
RM2L	0.45	0.71	0.90	0.66	1.80	0.67	3.60	0.63
RM2M	0.45	0.70	0.90	0.65	1.80	0.64	3.60	0.64
RM2H	0.45	0.69	0.90	0.65	1.80	0.64	3.60	0.64
URML								
URMM								
MH	0.38	0.66	0.75	0.67	1.50	0.67	3.00	0.67

Table 6.6b Special Building Nonstructural Acceleration-Sensitive Fragility - Moderate-Code Seismic Design Level

Building Type	Median Spectral Acceleration (g) and Logstandard Deviation (Beta)							
	Slight		Moderate		Extensive		Complete	
	Median	Beta	Median	Beta	Median	Beta	Median	Beta
W1	0.38	0.71	0.75	0.68	1.50	0.68	3.00	0.65
W2	0.38	0.67	0.75	0.68	1.50	0.68	3.00	0.68
S1L	0.38	0.67	0.75	0.67	1.50	0.68	3.00	0.68
S1M	0.38	0.67	0.75	0.67	1.50	0.67	3.00	0.67
S1H	0.38	0.67	0.75	0.66	1.50	0.66	3.00	0.66
S2L	0.38	0.66	0.75	0.66	1.50	0.68	3.00	0.68
S2M	0.38	0.65	0.75	0.65	1.50	0.64	3.00	0.64
S2H	0.38	0.65	0.75	0.65	1.50	0.65	3.00	0.65
S3	0.38	0.66	0.75	0.66	1.50	0.66	3.00	0.66
S4L	0.38	0.67	0.75	0.66	1.50	0.65	3.00	0.65
S4M	0.38	0.65	0.75	0.65	1.50	0.65	3.00	0.65
S4H	0.38	0.65	0.75	0.65	1.50	0.65	3.00	0.65
S5L								
S5M								
S5H								
C1L	0.38	0.68	0.75	0.66	1.50	0.68	3.00	0.68
C1M	0.38	0.66	0.75	0.65	1.50	0.65	3.00	0.65
C1H	0.38	0.65	0.75	0.65	1.50	0.65	3.00	0.65
C2L	0.38	0.67	0.75	0.67	1.50	0.67	3.00	0.67
C2M	0.38	0.65	0.75	0.64	1.50	0.66	3.00	0.66
C2H	0.38	0.65	0.75	0.64	1.50	0.64	3.00	0.64
C3L								
C3M								
C3H								
PC1	0.38	0.67	0.75	0.67	1.50	0.65	3.00	0.65
PC2L	0.38	0.66	0.75	0.66	1.50	0.64	3.00	0.64
PC2M	0.38	0.64	0.75	0.64	1.50	0.64	3.00	0.64
PC2H	0.38	0.64	0.75	0.65	1.50	0.65	3.00	0.65
RM1L	0.38	0.67	0.75	0.67	1.50	0.67	3.00	0.67
RM1M	0.38	0.65	0.75	0.64	1.50	0.66	3.00	0.66
RM2L	0.38	0.67	0.75	0.67	1.50	0.67	3.00	0.67
RM2M	0.38	0.65	0.75	0.64	1.50	0.66	3.00	0.66
RM2H	0.38	0.65	0.75	0.64	1.50	0.64	3.00	0.64
URML								
URMM								
MH	0.38	0.66	0.75	0.67	1.50	0.67	3.00	0.67

Table 6.6c Special Building Nonstructural Acceleration-Sensitive Fragility - Low-Code Seismic Design Level

Building Type	Median Spectral Acceleration (g) and Logstandard Deviation (Beta)							
	Slight		Moderate		Extensive		Complete	
	Median	Beta	Median	Beta	Median	Beta	Median	Beta
W1	0.30	0.71	0.60	0.68	1.20	0.66	2.40	0.65
W2	0.30	0.66	0.60	0.66	1.20	0.69	2.40	0.69
S1L	0.30	0.66	0.60	0.68	1.20	0.68	2.40	0.68
S1M	0.30	0.66	0.60	0.68	1.20	0.68	2.40	0.68
S1H	0.30	0.67	0.60	0.67	1.20	0.67	2.40	0.67
S2L	0.30	0.65	0.60	0.68	1.20	0.68	2.40	0.68
S2M	0.30	0.65	0.60	0.67	1.20	0.67	2.40	0.67
S2H	0.30	0.64	0.60	0.67	1.20	0.67	2.40	0.67
S3	0.30	0.65	0.60	0.67	1.20	0.67	2.40	0.67
S4L	0.30	0.65	0.60	0.68	1.20	0.68	2.40	0.68
S4M	0.30	0.64	0.60	0.68	1.20	0.68	2.40	0.68
S4H	0.30	0.64	0.60	0.67	1.20	0.67	2.40	0.67
S5L	0.30	0.65	0.60	0.68	1.20	0.68	2.40	0.68
S5M	0.30	0.64	0.60	0.67	1.20	0.67	2.40	0.67
S5H	0.30	0.64	0.60	0.67	1.20	0.67	2.40	0.67
C1L	0.30	0.65	0.60	0.68	1.20	0.68	2.40	0.68
C1M	0.30	0.64	0.60	0.67	1.20	0.67	2.40	0.67
C1H	0.30	0.67	0.60	0.67	1.20	0.67	2.40	0.67
C2L	0.30	0.66	0.60	0.66	1.20	0.65	2.40	0.65
C2M	0.30	0.63	0.60	0.65	1.20	0.65	2.40	0.65
C2H	0.30	0.63	0.60	0.66	1.20	0.66	2.40	0.66
C3L	0.30	0.65	0.60	0.67	1.20	0.67	2.40	0.67
C3M	0.30	0.63	0.60	0.66	1.20	0.66	2.40	0.66
C3H	0.30	0.63	0.60	0.67	1.20	0.67	2.40	0.67
PC1	0.30	0.66	0.60	0.65	1.20	0.65	2.40	0.65
PC2L	0.30	0.65	0.60	0.68	1.20	0.68	2.40	0.68
PC2M	0.30	0.63	0.60	0.67	1.20	0.67	2.40	0.67
PC2H	0.30	0.64	0.60	0.66	1.20	0.66	2.40	0.66
RM1L	0.30	0.66	0.60	0.66	1.20	0.65	2.40	0.65
RM1M	0.30	0.64	0.60	0.65	1.20	0.65	2.40	0.65
RM2L	0.30	0.66	0.60	0.66	1.20	0.66	2.40	0.66
RM2M	0.30	0.64	0.60	0.65	1.20	0.65	2.40	0.65
RM2H	0.30	0.63	0.60	0.65	1.20	0.65	2.40	0.65
URML	0.30	0.68	0.60	0.66	1.20	0.64	2.40	0.64
URMM	0.30	0.64	0.60	0.65	1.20	0.65	2.40	0.65
MH	0.38	0.66	0.75	0.67	1.50	0.67	3.00	0.67

6.4.4 Structural Fragility Curves - Equivalent Peak Ground Acceleration

Structural damage fragility curves are expressed in terms of an equivalent value of PGA (rather than spectral displacement) for evaluation of Special buildings that are components of lifelines. Only structural damage functions are developed based on PGA, since structural damage is considered the most appropriate measure of damage for lifeline facilities. Similar methods could be used to develop nonstructural damage functions based on PGA. In this case, capacity curves are not necessary to estimate building response and PGA is used directly as the PESH input to building fragility curves.

This section provides equivalent-PGA fragility curves for Special buildings based on the structural damage functions of Tables 6.4a - 6.4c and standard spectrum shape properties of Chapter 4. These functions have the same format and are based on the same approach and assumptions as those described in Section 5.4.4 for development equivalent-PGA fragility curves for Code buildings.

The values given in Tables 6.7a through 6.7c are appropriate for use in the evaluation of scenario earthquakes whose demand spectrum shape is based on, or similar to, large-magnitude, WUS ground shaking at soil sites (reference spectrum shape). For evaluation of building damage due to scenario earthquakes whose spectra are not similar to the reference spectrum shape, damage-state median parameters may be adjusted to better represent equivalent-PGA structural fragility for the spectrum shape of interest.

Median values of equivalent-PGA are adjusted for: (1) the site condition (if different from Site Class D) and (2) the ratio of long-period spectral response (i.e., S_{A1}) to PGA (if different from a value of 1.5, the ratio of S_{A1} to PGA of the reference spectrum shape). Damage-state variability is not adjusted assuming that the variability associated with ground shaking (although different for different source/site conditions) when combined with the uncertainty in damage-state threshold, is approximately the same for all demand spectrum shapes.

Equivalent-PGA medians, given in Tables 6.7a through 6.7c for the reference spectrum shape, are adjusted to represent other spectrum shapes using the spectrum shape ratios of Tables 5.14 and 5.15, the soil amplification factor, F_V, and Equation (5-6). In general, implementation of Equation (5-6) requires information on earthquake magnitude and source-to-site distance to estimate the spectrum shape ratio for rock sites, and 1-second period spectral acceleration at the site (to estimate the soil amplification factor). Note that for the following tables, shaded boxes indicate types that are not permitted by current seismic codes.

Table 6.7a Equivalent-PGA Structural Fragility - Special High-Code Seismic Design Level

Building Type	Median Equivalent-PGA (g) and Logstandard Deviation (Beta)							
	Slight		Moderate		Extensive		Complete	
	Median	Beta	Median	Beta	Median	Beta	Median	Beta
W1	0.32	0.64	0.78	0.64	2.00	0.64	3.22	0.64
W2	0.35	0.64	0.82	0.64	1.76	0.64	3.13	0.64
S1L	0.25	0.64	0.44	0.64	0.92	0.64	2.17	0.64
S1M	0.17	0.64	0.34	0.64	0.85	0.64	2.10	0.64
S1H	0.13	0.64	0.26	0.64	0.65	0.64	1.73	0.64
S2L	0.33	0.64	0.58	0.64	1.10	0.64	2.07	0.64
S2M	0.18	0.64	0.35	0.64	0.97	0.64	2.34	0.64
S2H	0.14	0.64	0.27	0.64	0.81	0.64	2.13	0.64
S3	0.19	0.64	0.36	0.64	0.79	0.64	1.44	0.64
S4L	0.34	0.64	0.54	0.64	1.04	0.64	1.91	0.64
S4M	0.21	0.64	0.37	0.64	0.98	0.64	2.27	0.64
S4H	0.16	0.64	0.32	0.64	0.90	0.64	2.29	0.64
S5L								
S5M								
S5H								
C1L	0.29	0.64	0.51	0.64	1.07	0.64	2.06	0.64
C1M	0.19	0.64	0.36	0.64	1.02	0.64	2.48	0.64
C1H	0.14	0.64	0.28	0.64	0.83	0.64	2.03	0.64
C2L	0.33	0.64	0.66	0.64	1.42	0.64	2.40	0.64
C2M	0.22	0.64	0.49	0.64	1.24	0.64	2.97	0.64
C2H	0.15	0.64	0.37	0.64	1.11	0.64	2.80	0.64
C3L								
C3M								
C3H								
PC1	0.25	0.64	0.48	0.64	1.02	0.64	1.86	0.64
PC2L	0.32	0.64	0.51	0.64	1.03	0.64	1.78	0.64
PC2M	0.22	0.64	0.40	0.64	0.92	0.64	2.25	0.64
PC2H	0.15	0.64	0.30	0.64	0.83	0.64	2.13	0.64
RM1L	0.39	0.64	0.65	0.64	1.52	0.64	2.53	0.64
RM1M	0.25	0.64	0.50	0.64	1.15	0.64	2.76	0.64
RM2L	0.34	0.64	0.59	0.64	1.41	0.64	2.36	0.64
RM2M	0.22	0.64	0.43	0.64	1.05	0.64	2.65	0.64
RM2H	0.15	0.64	0.30	0.64	0.89	0.64	2.58	0.64
URML								
URMM								
MH	0.16	0.64	0.26	0.64	0.45	0.64	0.88	0.64

Table 6.7b Equivalent-PGA Structural Fragility - Special Moderate-Code Seismic Design Level

Building Type	Median Equivalent-PGA (g) and Logstandard Deviation (Beta)							
	Slight		Moderate		Extensive		Complete	
	Median	Beta	Median	Beta	Median	Beta	Median	Beta
W1	0.32	0.64	0.59	0.64	1.32	0.64	2.08	0.64
W2	0.28	0.64	0.51	0.64	1.00	0.64	1.83	0.64
S1L	0.20	0.64	0.31	0.64	0.60	0.64	1.29	0.64
S1M	0.16	0.64	0.28	0.64	0.60	0.64	1.27	0.64
S1H	0.13	0.64	0.22	0.64	0.51	0.64	1.17	0.64
S2L	0.27	0.64	0.37	0.64	0.67	0.64	1.27	0.64
S2M	0.17	0.64	0.28	0.64	0.69	0.64	1.40	0.64
S2H	0.14	0.64	0.23	0.64	0.63	0.64	1.44	0.64
S3	0.18	0.64	0.26	0.64	0.46	0.64	0.86	0.64
S4L	0.26	0.64	0.36	0.64	0.61	0.64	1.17	0.64
S4M	0.18	0.64	0.29	0.64	0.69	0.64	1.33	0.64
S4H	0.16	0.64	0.26	0.64	0.66	0.64	1.42	0.64
S5L								
S5M								
S5H								
C1L	0.23	0.64	0.33	0.64	0.63	0.64	1.22	0.64
C1M	0.17	0.64	0.28	0.64	0.70	0.64	1.38	0.64
C1H	0.14	0.64	0.23	0.64	0.59	0.64	1.15	0.64
C2L	0.26	0.64	0.44	0.64	0.77	0.64	1.34	0.64
C2M	0.20	0.64	0.35	0.64	0.81	0.64	1.63	0.64
C2H	0.15	0.64	0.30	0.64	0.78	0.64	1.63	0.64
C3L								
C3M								
C3H								
PC1	0.24	0.64	0.33	0.64	0.63	0.64	1.05	0.64
PC2L	0.24	0.64	0.35	0.64	0.59	0.64	1.06	0.64
PC2M	0.19	0.64	0.29	0.64	0.62	0.64	1.27	0.64
PC2H	0.15	0.64	0.25	0.64	0.60	0.64	1.30	0.64
RM1L	0.31	0.64	0.44	0.64	0.79	0.64	1.33	0.64
RM1M	0.24	0.64	0.36	0.64	0.74	0.64	1.65	0.64
RM2L	0.28	0.64	0.41	0.64	0.74	0.64	1.27	0.64
RM2M	0.21	0.64	0.32	0.64	0.69	0.64	1.58	0.64
RM2H	0.15	0.64	0.25	0.64	0.64	0.64	1.53	0.64
URML								
URMM								
MH	0.16	0.64	0.26	0.64	0.45	0.64	0.88	0.64

Table 6.7c Equivalent-PGA Structural Fragility - Special Low-Code Seismic Design Level

Building Type	Median Equivalent-PGA (g) and Logstandard Deviation (Beta)							
	Slight		Moderate		Extensive		Complete	
	Median	Beta	Median	Beta	Median	Beta	Median	Beta
W1	0.28	0.64	0.50	0.64	1.00	0.64	1.51	0.64
W2	0.21	0.64	0.34	0.64	0.68	0.64	1.10	0.64
S1L	0.16	0.64	0.23	0.64	0.42	0.64	0.71	0.64
S1M	0.15	0.64	0.23	0.64	0.42	0.64	0.73	0.64
S1H	0.13	0.64	0.20	0.64	0.40	0.64	0.71	0.64
S2L	0.19	0.64	0.25	0.64	0.44	0.64	0.74	0.64
S2M	0.16	0.64	0.24	0.64	0.52	0.64	0.88	0.64
S2H	0.14	0.64	0.21	0.64	0.50	0.64	0.93	0.64
S3	0.14	0.64	0.18	0.64	0.30	0.64	0.57	0.64
S4L	0.19	0.64	0.23	0.64	0.38	0.64	0.68	0.64
S4M	0.16	0.64	0.23	0.64	0.47	0.64	0.81	0.64
S4H	0.15	0.64	0.23	0.64	0.48	0.64	0.87	0.64
S5L	0.18	0.64	0.26	0.64	0.41	0.64	0.68	0.64
S5M	0.14	0.64	0.24	0.64	0.50	0.64	0.80	0.64
S5H	0.13	0.64	0.24	0.64	0.51	0.64	0.84	0.64
C1L	0.17	0.64	0.22	0.64	0.39	0.64	0.67	0.64
C1M	0.15	0.64	0.23	0.64	0.48	0.64	0.80	0.64
C1H	0.13	0.64	0.20	0.64	0.39	0.64	0.66	0.64
C2L	0.19	0.64	0.27	0.64	0.44	0.64	0.79	0.64
C2M	0.16	0.64	0.26	0.64	0.56	0.64	0.93	0.64
C2H	0.14	0.64	0.25	0.64	0.56	0.64	0.96	0.64
C3L	0.17	0.64	0.25	0.64	0.39	0.64	0.65	0.64
C3M	0.14	0.64	0.23	0.64	0.46	0.64	0.75	0.64
C3H	0.12	0.64	0.22	0.64	0.48	0.64	0.79	0.64
PC1	0.18	0.64	0.24	0.64	0.38	0.64	0.65	0.64
PC2L	0.18	0.64	0.23	0.64	0.36	0.64	0.66	0.64
PC2M	0.16	0.64	0.22	0.64	0.45	0.64	0.79	0.64
PC2H	0.14	0.64	0.21	0.64	0.45	0.64	0.81	0.64
RM1L	0.22	0.64	0.29	0.64	0.44	0.64	0.80	0.64
RM1M	0.19	0.64	0.26	0.64	0.50	0.64	0.92	0.64
RM2L	0.20	0.64	0.27	0.64	0.41	0.64	0.77	0.64
RM2M	0.17	0.64	0.24	0.64	0.47	0.64	0.88	0.64
RM2H	0.14	0.64	0.22	0.64	0.49	0.64	0.92	0.64
URML	0.19	0.64	0.28	0.64	0.47	0.64	0.68	0.64
URMM	0.14	0.64	0.22	0.64	0.38	0.64	0.70	0.64
MH	0.16	0.64	0.26	0.64	0.45	0.64	0.88	0.64

6.5 Damage Due to Ground Failure - Special Buildings

Damage to Special buildings due to ground failure is assumed to be the same as the damage to Code buildings for the same amount of permanent ground deformation (PGD). Fragility curves developed in Section 5.5 for Code buildings are also appropriate for prediction of damage to Special buildings due to ground failure.

6.6 Evaluation of Building Damage - Essential Facilities

6.6.1 Overview

Special building capacity and fragility curves for structural and nonstructural systems are used to predict essential facility damage when the user is able to determine that the essential facility is superior to a typical building of the model building type and design level of interest. If such a determination cannot be made by the user, then the Code building functions of Chapter 5 are used to evaluate essential building damage. These criteria are summarized in Table 6.8.

Table 6.8 Criteria for Evaluating Essential Facility Damage

Evaluate Essential Facility Using:	User Deems Essential Facility to be:
Code building damage functions (High-Code, Moderate-Code, Low-Code and Pre-Code functions of Chapter 5)	Typical of the model building type and seismic design level of interest (i.e., no special seismic protection of components)
Special building damage functions (High-Code, Moderate-Code and Low-Code functions of Chapter 6)	Superior to the model building type and seismic design level of interest (e.g., 50 percent stronger lateral-force-resisting structural system, and special anchorage and bracing of nonstructural components)

During an earthquake, the essential facilities may be damaged either by ground shaking, ground failure, or both. Essential facilities are evaluated separately for the two modes of, ground shaking and ground failure, and the resulting damage-state probabilities combined for evaluation of loss.

6.6.2 Damage Due to Ground Shaking

Damage to essential facilities due to ground shaking uses the same methods as those described in Section 5.6.2 for Code buildings, with the exception that Special buildings are assumed to have less degradation and greater effective damping than Code buildings.

6.6.2.1 Demand Spectrum Reduction for Effective Damping - Special Buildings

Demand spectra for evaluation of damage to Special buildings are constructed using the same approach, assumptions and formulas as those described in Section 5.6.2.1 for Code buildings, except values of the degradation factor, κ, that defines the effective amount of hysteretic damping as a function of duration are different for Special buildings. Degradation factors for Special buildings are given in Table 6.9.

Figure 6.5 shows typical demand spectra (spectral acceleration plotted as a function of spectral displacement) for three demand levels. These three demand levels represent Short (κ = 0.90), Moderate (κ = 0.60) and Long (κ = 0.40) duration ground shaking, respectively. Also shown in the figure is the building capacity curve of a low-rise Special building (Moderate-Code seismic design) that was used to estimate effective damping. The intersection of the capacity curve with each of the three demand spectra illustrates the significance of duration (damping) on building response.

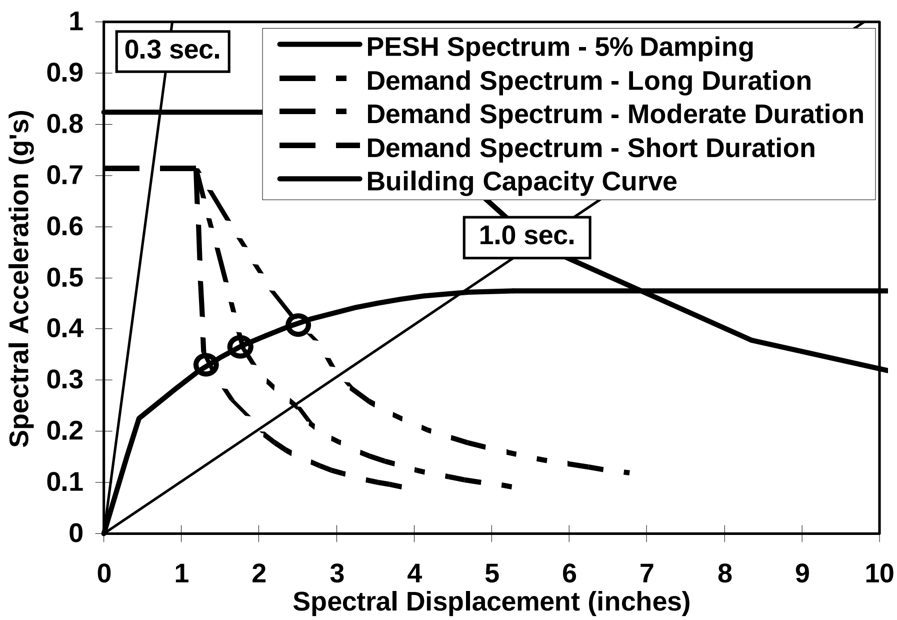


Figure 6.5 Example Demand Spectra - Special Building (M = 7.0 at 20 km, WUS, Site Class E).

Comparison of Figure 6.5 with Figure 5.7 (same example building and PESH demand, except capacity curve and damping represents Code building properties) illustrates the significance of increased strength and damping (reduced degradation) of Special buildings on the reduction of building displacement. In this case, the Special building displaces only about one-half as much as a comparable Code building for the same level of PESH demand. Forces on nonstructural acceleration-sensitive components are not reduced, but are slightly increased due to the higher strength of the Special building.

Table 6.9 Special Building Degradation Factor (κ) as a Function of Short, Moderate and Long Earthquake Duration

Building Type		High-Code Design			Moderate-Code Design			Low-Code Design		
No.	Label	Short	Moderate	Long	Short	Moderate	Long	Short	Moderate	Long
1	W1	1.0	1.0	0.7	1.0	0.8	0.5	0.9	0.6	0.3
2	W2	1.0	0.8	0.6	0.9	0.6	0.4	0.8	0.4	0.2
3	S1L	1.0	0.8	0.6	0.9	0.6	0.4	0.8	0.4	0.2
4	S1M	1.0	0.8	0.6	0.9	0.6	0.4	0.8	0.4	0.2
5	S1H	1.0	0.8	0.6	0.9	0.6	0.4	0.8	0.4	0.2
6	S2L	0.8	0.6	0.4	0.7	0.5	0.3	0.6	0.4	0.2
7	S2M	0.8	0.6	0.4	0.7	0.5	0.3	0.6	0.4	0.2
8	S2H	0.8	0.6	0.4	0.7	0.5	0.3	0.6	0.4	0.2
9	S3	0.8	0.6	0.4	0.7	0.5	0.3	0.6	0.4	0.2
10	S4L	0.8	0.6	0.4	0.7	0.5	0.3	0.6	0.4	0.2
11	S4M	0.8	0.6	0.4	0.7	0.5	0.3	0.6	0.4	0.2
12	S4H	0.8	0.6	0.4	0.7	0.5	0.3	0.6	0.4	0.2
13	S5L	0.6	0.4	0.2	0.6	0.4	0.2	0.6	0.4	0.2
14	S5M	0.6	0.4	0.2	0.6	0.4	0.2	0.6	0.4	0.2
15	S5H	0.6	0.4	0.2	0.6	0.4	0.2	0.6	0.4	0.2
16	C1L	1.0	0.8	0.6	0.9	0.6	0.4	0.8	0.4	0.2
17	C1M	1.0	0.8	0.6	0.9	0.6	0.4	0.8	0.4	0.2
18	C1H	1.0	0.8	0.6	0.9	0.6	0.4	0.8	0.4	0.2
19	C2L	1.0	0.8	0.6	0.9	0.6	0.4	0.8	0.4	0.2
20	C2M	1.0	0.8	0.6	0.9	0.6	0.4	0.8	0.4	0.2
21	C2H	1.0	0.8	0.6	0.9	0.6	0.4	0.8	0.4	0.2
22	C3L	0.6	0.4	0.2	0.6	0.4	0.2	0.6	0.4	0.2
23	C3M	0.6	0.4	0.2	0.6	0.4	0.2	0.6	0.4	0.2
24	C3H	0.6	0.4	0.2	0.6	0.4	0.2	0.6	0.4	0.2
25	PC1	0.8	0.6	0.4	0.7	0.5	0.3	0.6	0.4	0.2
26	PC2L	0.8	0.6	0.4	0.7	0.5	0.3	0.6	0.4	0.2
27	PC2M	0.8	0.6	0.4	0.7	0.5	0.3	0.6	0.4	0.2
28	PC2H	0.8	0.6	0.4	0.7	0.5	0.3	0.6	0.4	0.2
29	RM1L	1.0	0.8	0.6	0.9	0.6	0.4	0.8	0.4	0.2
30	RM1M	1.0	0.8	0.6	0.9	0.6	0.4	0.8	0.4	0.2
31	RM2L	1.0	0.8	0.6	0.9	0.6	0.4	0.8	0.4	0.2
32	RM2M	1.0	0.8	0.6	0.9	0.6	0.4	0.8	0.4	0.2
33	RM2H	1.0	0.8	0.6	0.9	0.6	0.4	0.8	0.4	0.2
34	URML	0.6	0.4	0.2	0.6	0.4	0.2	0.6	0.4	0.2
35	URMM	0.6	0.4	0.2	0.6	0.4	0.2	0.6	0.4	0.2
36	MH	0.9	0.6	0.4	0.9	0.6	0.4	0.9	0.6	0.4

6.6.2.2 Damage State Probability

Structural and nonstructural fragility curves of essential facilities are evaluated for spectral displacement and spectral acceleration defined by the intersection of the capacity and demand curves. Each of these curves describe the cumulative probability of being in or exceeding, a particular damage state. Nonstructural components (both drift- and acceleration-sensitive components) may, in some cases, be dependent on the structural damage state (e.g., Complete structural damage may cause Complete nonstructural damage). The Methodology assumes nonstructural damage states to be independent of structural damage states. Cumulative probabilities are differenced to obtain discrete probabilities of being in each of the five damage states. This process is shown schematically in Figure 6.6.

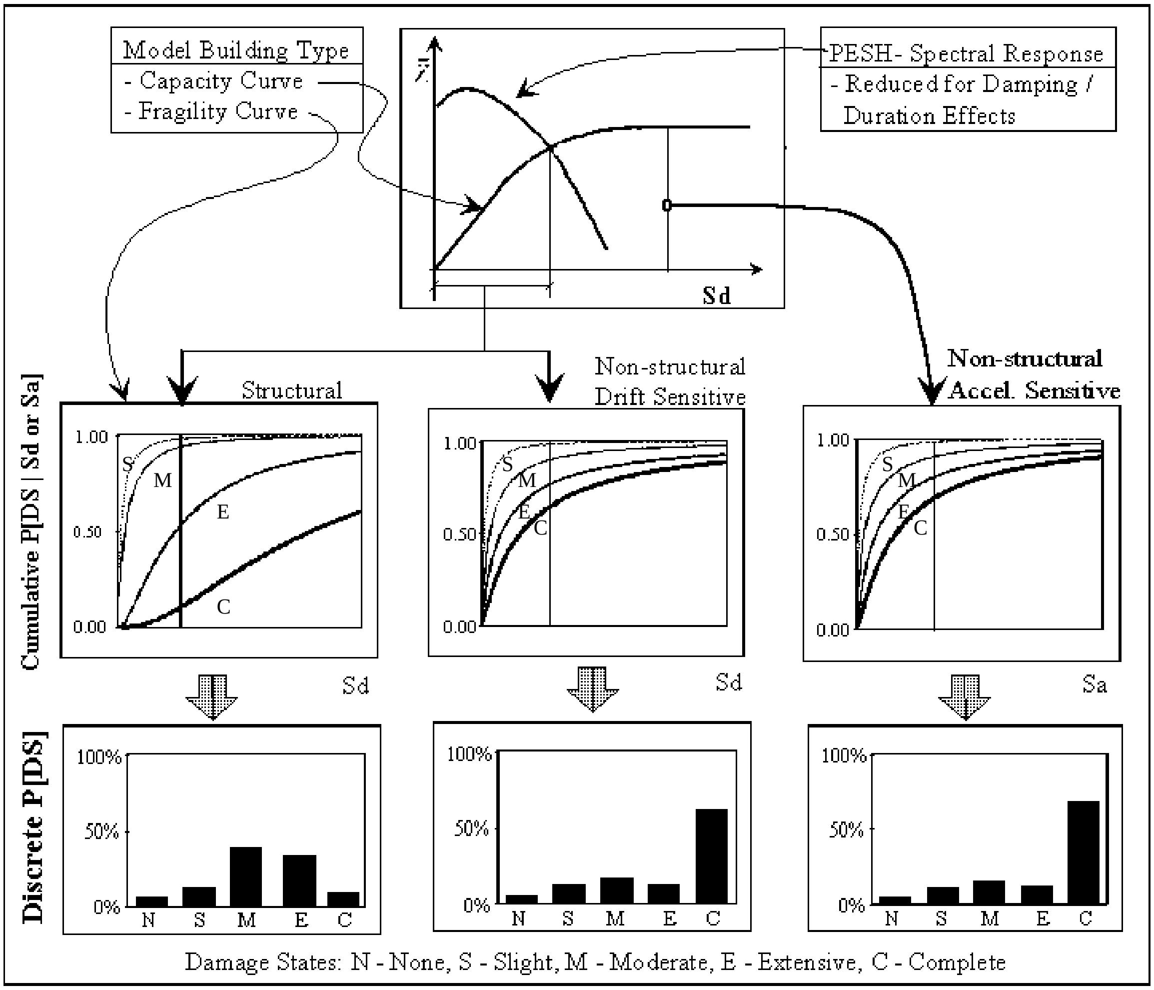


Figure 6.6 Example Essential Facility Damage Estimation Process.

6.6.3 Combined Damage Due to Ground Failure and Ground Shaking

Damage to essential facilities is based either on Code building damage functions or Special building damage functions. Code building damage due to ground shaking is combined with damage due to ground shaking as specified in Section 5.6.3. Special building damage due to ground failure (Section 6.5.2) is combined with damage due to ground shaking (Section 6.6.2.2) using the same approach, assumptions and formulas as those given in Section 5.6.3 for Code buildings.

6.6.4 Combined Damage to Essential Facilities

Combined ground shaking/ground failure damage to the model building type and design level of interest (either a Special or a Code building) represents combined damage to the essential facility.

6.7 Guidance for Expert Users

This section provides guidance for users who are seismic/structural experts interested in modifying essential facility damage functions supplied with the methodology. This section also provides the expert user with guidance regarding the selection of the appropriate mix of design levels for the region of interest.

6.7.1 Selection of Representative Seismic Design Level

The methodology permits the user to select the seismic design level considered appropriate for each essential facility and to designate the facility as a Special building, when designed and constructed to above-Code standards. In general, performance of essential facilities is not expected to be better than the typical (Code) building of the representative model building type. Exceptions to this generalization include California hospitals of recent (post-1973) construction. If the user is not able to determine that the essential facility is significantly better than average, then the facility should be modeled using Code building damage functions (i.e., same methods as those developed in Chapter 5 for general building stock).

Table 6.10 provides guidance for selecting appropriate building damage functions for essential facilities based on design vintage. These guidelines are applicable to the following facilities:

1. hospitals and other medical facilities having surgery or emergency treatment areas,
2. fire and police stations, and
3. municipal government disaster operation and communication centers deemed (for design) to be vital in emergencies,

provided that seismic codes (e.g., *Uniform Building Code*) were adopted and enforced in the study area of interest. Such adoption and enforcement is generally true for jurisdictions of California, but may not be true other areas.

Table 6.10 Guidelines for Selection of Damage Functions for Essential Facilities Based on *UBC* Seismic Zone and Building Age

***UBC* Seismic Zone (NEHRP Map Area)**	**Post-1973**	**1941 - 1973**	**Pre-1941**
Zone 4 (Map Area 7)	Special High-Code	Moderate-Code	Pre-Code (W1 = Moderate-Code)
Zone 3 (Map Area 6)	Special Moderate-Code	Moderate-Code	Pre-Code (W1 = Moderate-Code)
Zone 2B (Map Area 5)	Moderate-Code	Low-Code	Pre-Code (W1 = Low-Code)
Zone 2A (Map Area 4)	Low-Code	Low-Code	Pre-Code (W1 = Low-Code)
Zone 1 Map Area 2/3)	Low-Code	Pre-Code (W1 = Low-Code)	Pre-Code (W1 = Low-Code)
Zone 0 (Map Area 1)	Pre-Code (W1 = Low-Code)	Pre-Code (W1 = Low-Code)	Pre-Code (W1 = Low-Code)

The guidelines given in Table 6.1 assume that essential buildings in the study region are not designed for wind. The user should consider the possibility that mid-rise and high-rise facilities could be designed for wind and may have considerable lateral strength, even if not designed for earthquake. Users must be knowledgeable about the type and history of construction in the study region of interest and apply engineering judgment in assigning essential facilities to a building type and seismic design level.

6.7.2 High Potential Loss Facilities

6.7.2.1 Introduction

This section describes damage evaluation of high potential loss (HPL) facilities. HPL facilities are likely to cause heavy earthquake losses, if significantly damaged. Examples of such facilities include nuclear power plants, certain military and industrial facilities, dams, etc.

6.7.2.2 Input Requirements and Output Information

The importance of these facilities (in terms of potential earthquake losses) suggests that damage assessment be done in a special way as compared to ordinary buildings. Each HPL facility should be treated on an individual basis by users who have sufficient expertise to evaluate damage to such facilities. Required input to the damage evaluation module includes the following items:

- capacity curves that represents median (typical) properties of the HPL facility structure, or a related set of engineering parameters, such as period, yield strength, and ultimate capacity, that may be used by seismic/structural engineering experts with the methods of Chapter 5 to select representative damage functions,

- fragility curves for the HPL facility under consideration, or related set engineering parameters, that can be used by seismic/structural engineering experts with the methods of Chapter 5 to select appropriate damage functions.

The direct output (damage estimate) from implementation of the fragility curves is an estimate of the probability of being in, or exceeding, each damage state for the given level of ground shaking. This output is used directly as an input to other damage or loss estimation methods or combined with inventory information to predict the distribution of damage as a function of facility type, and geographical location. In the latter case, the number and geographical location of facilities of interest would be a required input to the damage estimation method.

6.7.2.3 Form of Damage Functions and Damage Evaluation

The form of user-supplied HPL facility damage functions should be the same as that of buildings (Chapter 5) and their use in the methodology would be similar to that of essential facilities.

6.8 Essential Facility and HPL Damage References

Refer to Section 5.8 for building damage references.

6.9 Restoration Curves

Restoration curves are based on generic ATC-13 data for the social function classifications of interest and are approximated as normal curves characterized by a mean and a standard deviation. The parameters of these restoration curves are given in Table 6.11 and are fully user-editable

Table 6.11 Generic Restoration Functions for Essential Facilities

EF Class	Description	Slight Mean	Slight Sigma	Moderate Mean	Moderate Sigma	Extensive Mean	Extensive Sigma	Complete Mean	Complete Sigma
EDFLT	Default for Emergency Response Facility	5	1	20	2	90	10	180	20
EFEO	Emergency Operation Centers	5	1	20	2	90	10	180	20
EFFS	Fire Station	5	1	20	2	90	10	180	20
EFHL	Large Hospital (greater than 150 beds)	5	1	20	2	90	10	180	20
EFHM	Medium Hospital (50 to 150 Beds)	5	1	20	2	90	10	180	20
EFHS	Small Hospital (less than 50 Beds)	5	1	20	2	90	10	180	20
EFMC	Medical Clinics and Labs	5	1	20	2	90	10	180	20
EFPS	Police Station	5	1	20	2	90	10	180	20
EFS1	Grade Schools (Primary and High Schools)	5	1	20	2	90	10	180	20
EFS2	Colleges/Universities	5	1	20	2	90	10	180	20
FDFLT	Default for Fire Station	5	1	20	2	90	10	180	20
MDFL	Default for Medical	5	1	20	2	90	10	180	20

T									
PDFLT	Default for Police	5	1	20	2	90	10	180	20
SDFLT	Default for School	5	1	20	2	90	10	180	20

Chapter 7
Direct Physical Damage to Lifelines - Transportation Systems

This chapter describes the methodology for estimating direct physical damage to Transportation Systems, which include the following seven systems:

- Highway
- Railway
- Light Rail
- Bus
- Port
- Ferry
- Airport

The flowchart of the overall methodology, highlighting the transportation system module and its relationship to other modules, is shown in Flowchart 7.1.

7.1 Highway Transportation System

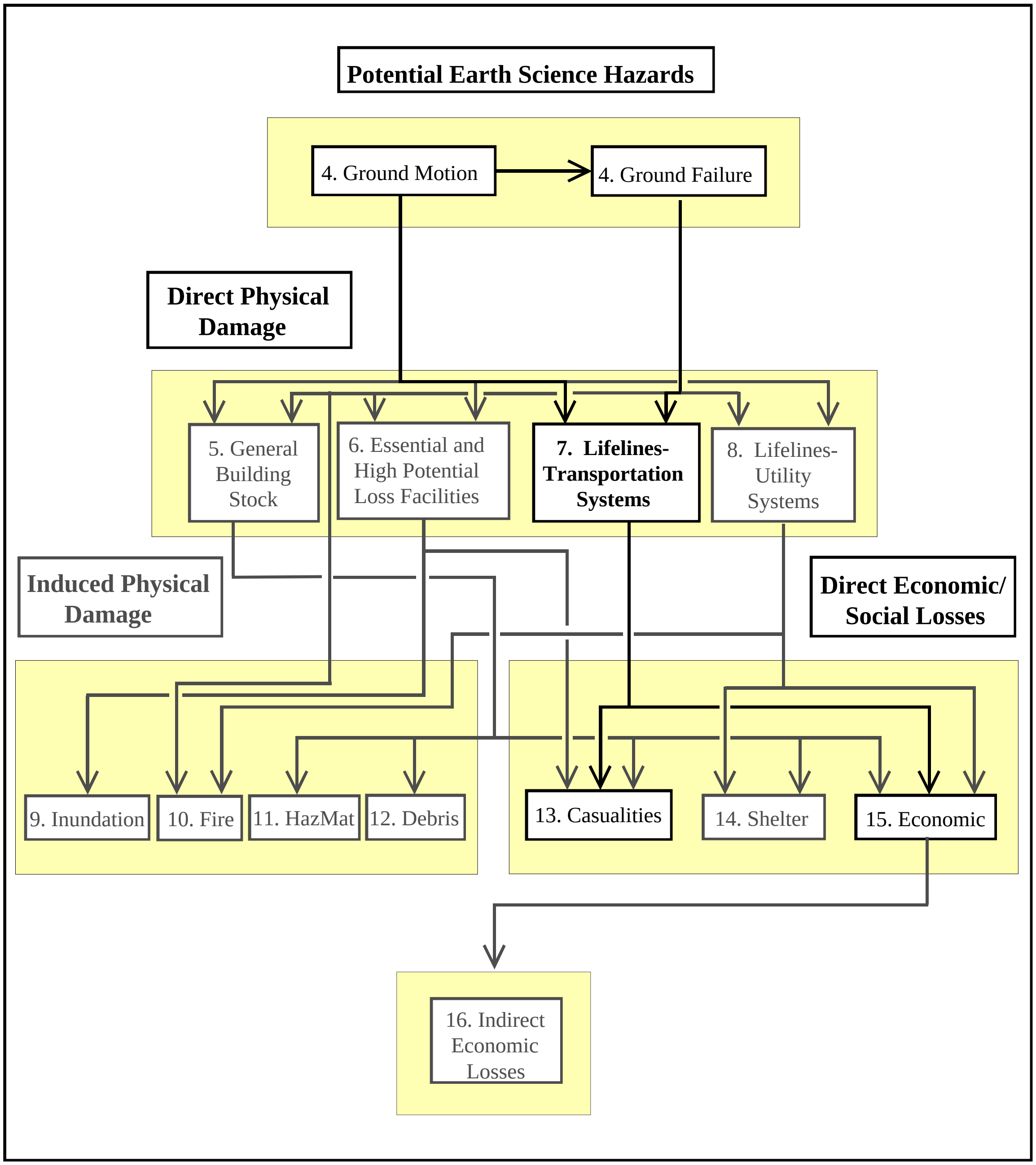
7.1.1 Introduction

This section presents an earthquake loss estimation methodology for a highway transportation system. This system consists of roadways, bridges and tunnels. Roads located on soft soil or fill or which cross a surface fault rupture can experience failure resulting in loss of functionality. Bridges that fail usually result in significant disruption to the transportation network, especially bridges that cross waterways. Likewise, tunnels are often not redundant, and major disruption to the transportation system is likely to occur should a tunnel become non-functional. Past earthquake damage reveals that bridges and tunnels are vulnerable to both ground shaking and ground failure, while roads are significantly affected by ground failure alone.

7.1.2 Scope

The scope of this section includes development of methods for estimation of earthquake damage to a highway transportation system given knowledge of the system's components (i.e., roadways, bridges, or tunnels), the classification of each component (e.g., for roadways, whether the road is a major road or urban road), and the ground motion (i.e. peak ground acceleration and/or permanent ground deformation).

Damage states describing the level of damage to each highway system component are defined (i.e. slight/minor, moderate, extensive or complete). Damage states are related to a damage ratio defined as the ratio of repair to replacement cost for evaluation of direct economic loss. Component restoration curves are provided for each damage state to evaluate loss of function. Restoration curves describe the fraction or percentage of the component that is expected to be open or operational as a function of time following the earthquake. For example, an extensively damaged roadway link might be closed (0% functional) immediately following the earthquake, but 100% functional after 30 days.



Flowchart 7.1 Transportation System Damage Relationship to Other Modules of the Earthquake Loss Estimation Methodology

Fragility curves are developed for each type of highway system component. These curves describe the probability of reaching or exceeding each damage state given the level of ground motion.

7.1.3 Input Requirements and Output Information

Descriptions of required input to estimate damages to each highway system are given below.

Roadways

- Geographical location of roadway links (longitude and latitude of end nodes)
- Permanent ground deformation (PGD) at roadway link
- Roadway classification

Bridges

- Geographical location of bridge [longitude and latitude]
- Bridge classification
- Spectral accelerations at 0.3 sec and 1.0 sec, and PGD at bridge
- Peak Ground Acceleration (for PGD-related computations)

Tunnels

- Geographical location of tunnels [longitude and latitude]
- PGA and PGD at tunnel
- Tunnel Classification

Direct damage output for highway systems includes probability estimates of (1) component functionality and (2) physical damage expressed in terms of the component's damage ratio. Note that damage ratios, which are input to direct economic loss methods, are described in Chapter 15.

Component functionality is described by the probability of damage state (immediately following the earthquake) and by the associated fraction or percentage of the component that is expected to be functional after a specified period of time. For example, a roadway link might be found to have a 0.50 probability of extensive damage and on this basis would have a 0.50 probability that the road would be: (1) closed immediately, (2) partially open after a 3-day restoration period and (3) fully open after a 1-month restoration period.

Interdependence of components on overall system functionality is not addressed by the methodology. Such considerations require a network system analysis that would be performed separately by a highway system expert.

7.1.4 Form of Damage Functions

Damage functions or fragility curves for all three highway system components mentioned above are modeled as lognormally-distributed functions that give the probability of reaching or exceeding different damage states for a given level of ground motion or ground failure. Each fragility curve is characterized by a median value of ground motion or ground failure and an associated dispersion factor (lognormal standard deviation). Ground motion is quantified in terms of peak ground acceleration (PGA) and spectral acceleration (Sa), and ground failure is quantified in terms of permanent ground displacement (PGD).

- For roadways, fragility curves are defined in terms of PGD.
- For bridges, fragility curves are defined in terms of Sa (0.3 sec), Sa(1.0 sec) and PGD.
- For tunnels, fragility curves are defined in terms of PGA and PGD.

Definitions of various damage states and the methodology used in deriving all these fragility curves are presented in the following sections.

7.1.5 Description of Highway Components

As mentioned previously, a highway system is composed of three components: roadways, bridges and tunnels. In this section, a brief description of each is given.

Roadways

Roadways are classified as major roads and urban roads. Major roads include interstate and state highways and other roads with four lanes or more. Parkways are also classified as major roads. Urban roads include intercity roads and other roads with two lanes.

Bridges

Bridges are classified based on the following structural characteristics:

- Seismic Design
- Number of spans: single vs. multiple span bridges
- Structure type: concrete, steel, others
- Pier type: multiple column bents, single column bents and pier walls
- Abutment type and bearing type: monolithic vs. non-monolithic; high rocker bearings, low steel bearings and neoprene rubber bearings
- Span continuity: continuous, discontinuous (in-span hinges), and simply supported.

The seismic design of a bridge is taken into account in terms of the (*i*) spectrum modification factor, (*ii*) strength reduction factor due to cyclic motion, (*iii*) drift limits, and (*iv*) the longitudinal reinforcement ratio.

This classification scheme incorporates various parameters that affect damage into fragility analysis and provides a means to obtain better fragility curves when data become available. A total of 28 classes (HWB1 through HWB28) are defined this way. These classes differentiate between the different bridge characteristics found in the National Bridge Inventory (NBI).

Tables 7.1.a and 7.1.b summarize the key NBI characteristics used, while Table 7.2 presents the 28 classes derived for Hazus. Please refer to Table 3.6 in Chapter 3 for the full definitions of these bridges.

Table 7.1.a Bridge material Classes in NBI [NBI, 1988]

Code	Description
1	Concrete
2	Concrete continuous
3	Steel
4	Steel continuous
5	Prestressed concrete
6	Prestressed concrete continuous
7	Timber
8	Masonry
9	Aluminium, Wrought Iron, or Cast Iron
0	Other

Table 7.1.b Bridge Types in NBI [NBI, 1988]

Code	Description
01	Slab
02	Stringer/Multi-beam or Girder
03	Girder and Floor beam System
04	Tee Beam
05	Box Beam or Girders - Multiple
06	Box Beam or Girders – single or Spread
07	Frame
08	Orthotropic
09	Truss – Deck
10	Truss – Thru
11	Arch – Deck
12	Arch – Thru
13	Suspension
14	Stayed Girder
15	Movable – Lift
16	Movable – Bascule
17	Movable – Swing
18	Tunnel
19	Culvert
20	Mixed Types (applicable only to approach spans)
21	Segmental Box Girder
22	Channel Beam
00	Other

Table 7.2 Hazus Bridge Classification Scheme

CLASS	NBI Class	State	Year Built	# Spans	Length of Max. Span (meter)	Length less than 20 m	K_{3D} (See note below)	I_{shape} (See note below)	Design	Description
HWB1	All	Non-CA	< 1990		> 150	N/A	EQ1	0	Conventional	Major Bridge - Length > 150m
HWB1	All	CA	< 1975		> 150	N/A	EQ1	0	Conventional	Major Bridge - Length > 150m
HWB2	All	Non-CA	>= 1990		> 150	N/A	EQ1	0	Seismic	Major Bridge - Length > 150m
HWB2	All	CA	>= 1975		> 150	N/A	EQ1	0	Seismic	Major Bridge - Length > 150m
HWB3	All	Non-CA	< 1990	1		N/A	EQ1	1	Conventional	Single Span
HWB3	All	CA	< 1975	1		N/A	EQ1	1	Conventional	Single Span
HWB4	All	Non-CA	>= 1990	1		N/A	EQ1	1	Seismic	Single Span
HWB4	All	CA	>= 1975	1		N/A	EQ1	1	Seismic	Single Span
HWB5	101-106	Non-CA	< 1990			N/A	EQ1	0	Conventional	Multi-Col. Bent, Simple Support - Concrete
HWB6	101-106	CA	< 1975			N/A	EQ1	0	Conventional	Multi-Col. Bent, Simple Support - Concrete
HWB7	101-106	Non-CA	>= 1990			N/A	EQ1	0	Seismic	Multi-Col. Bent, Simple Support - Concrete
HWB7	101-106	CA	>= 1975			N/A	EQ1	0	Seismic	Multi-Col. Bent, Simple Support - Concrete
HWB8	205-206	CA	< 1975			N/A	EQ2	0	Conventional	Single Col., Box Girder - Continuous Concrete
HWB9	205-206	CA	>= 1975			N/A	EQ3	0	Seismic	Single Col., Box Girder - Continuous Concrete
HWB10	201-206	Non-CA	< 1990			N/A	EQ2	1	Conventional	Continuous Concrete
HWB10	201-206	CA	< 1975			N/A	EQ2	1	Conventional	Continuous Concrete
HWB11	201-206	Non-CA	>= 1990			N/A	EQ3	1	Seismic	Continuous Concrete
HWB11	201-206	CA	>= 1975			N/A	EQ3	1	Seismic	Continuous Concrete
HWB12	301-306	Non-CA	< 1990			No	EQ4	0	Conventional	Multi-Col. Bent, Simple Support - Steel
HWB13	301-306	CA	< 1975			No	EQ4	0	Conventional	Multi-Col. Bent, Simple Support - Steel
HWB14	301-306	Non-CA	>= 1990			N/A	EQ1	0	Seismic	Multi-Col. Bent, Simple Support - Steel
HWB14	301-306	CA	>= 1975			N/A	EQ1	0	Seismic	Multi-Col. Bent, Simple Support - Steel
HWB15	402-410	Non-CA	< 1990			No	EQ5	1	Conventional	Continuous Steel
HWB15	402-410	CA	< 1975			No	EQ5	1	Conventional	Continuous Steel
HWB16	402-410	Non-CA	>= 1990			N/A	EQ3	1	Seismic	Continuous Steel
HWB16	402-410	CA	>= 1975			N/A	EQ3	1	Seismic	Continuous Steel

Table 7.2 Hazus Bridge Classification Scheme (Continued)

CLASS	NBI Class	State	Year Built	# Spans	Length of Max. Span (meter)	Length less than 20 m	K_{3D} (notes below)	I_{shape} (notes below)	Design	Description
HWB17	501-506	Non-CA	< 1990			N/A	EQ1	0	Conventional	Multi-Col. Bent, Simple Support - Prestressed Concrete
HWB18	501-506	CA	< 1975			N/A	EQ1	0	Conventional	Multi-Col. Bent, Simple Support - Prestressed Concrete
HWB19	501-506	Non-CA	>= 1990			N/A	EQ1	0	Seismic	Multi-Col. Bent, Simple Support - Prestressed Concrete
HWB19	501-506	CA	>= 1975			N/A	EQ1	0	Seismic	Multi-Col. Bent, Simple Support - Prestressed Concrete
HWB20	605-606	CA	< 1975			N/A	EQ2	0	Conventional	Single Col., Box Girder - Prestressed Continuous Concrete
HWB21	605-606	CA	>= 1975			N/A	EQ3	0	Seismic	Single Col., Box Girder - Prestressed Continuous Concrete
HWB22	601-607	Non-CA	< 1990			N/A	EQ2	1	Conventional	Continuous Concrete
HWB22	601-607	CA	< 1975			N/A	EQ2	1	Conventional	Continuous Concrete
HWB23	601-607	Non-CA	>= 1990			N/A	EQ3	1	Seismic	Continuous Concrete
HWB23	601-607	CA	>= 1975			N/A	EQ3	1	Seismic	Continuous Concrete
HWB24	301-306	Non-CA	< 1990			Yes	EQ6	0	Conventional	Multi-Col. Bent, Simple Support - Steel
HWB25	301-306	CA	< 1975			Yes	EQ6	0	Conventional	Multi-Col. Bent, Simple Support - Steel
HWB26	402-410	Non-CA	< 1990			Yes	EQ7	1	Conventional	Continuous Steel
HWB27	402-410	CA	< 1975			Yes	EQ7	1	Conventional	Continuous Steel
HWB28										All other bridges that are not classified

EQ1 through EQ7 in Table 7.2 are equations for evaluating $K_{3D.}$ K_{3D} is a factor that modifies the piers' 2-dimensional capacity to allow for the 3-dimensional arch action in the deck. All of the equations have the same functional form; $K_{3D} = 1 + A / (N – B)$, where N is the number of spans and the parameters A and B are given in table 7.3.

The I_{shape} term (given in table 7.2) is a Boolean indicator. The K_{shape} factor is the modifier that converts cases for short periods to an equivalent spectral amplitude at T=1.0 second. When $I_{shape} = 0$, the K_{shape} factor does not apply. When $I_{shape} = 1$, the K_{shape} factor applies. Later in this section, the use of the K_{shape} factor will be illustrated through an example.

The 28 bridge classes in Table 7.2 (HWB1 through HWB28) reflect the maximum number of combinations for 'standard' bridge classes. Attributes such as the skeweness and number of spans are accounted for in the evaluation of damage potential through a modification scheme that is presented later in this section.

Table 7.3 Coefficients for Evaluating K_{3D}

Equation	A	B	K_{3D}
EQ1	0.25	1	1 + 0.25 / (N – 1)
EQ2	0.33	0	1 + 0.33 / (N)
EQ3	0.33	1	1 + 0.33 / (N – 1)
EQ4	0.09	1	1 + 0.09 / (N – 1)
EQ5	0.05	0	1 + 0.05 / (N)
EQ6	0.20	1	1 + 0.20 / (N – 1)
EQ7	0.10	0	1 + 0.10 / (N)

Tunnels

Tunnels are classified as bored/drilled or cut & cover.

7.1.6 Definitions of Damage States

A total of five damage states are defined for highway system components. These are none (ds_1), slight/minor (ds_2), moderate (ds_3), extensive (ds_4) and complete (ds_5).

Slight/Minor Damage (ds_2)

- For roadways, ds_2 is defined by slight settlement (few inches) or offset of the ground.
- For bridges, ds_2 is defined by minor cracking and spalling to the abutment, cracks in shear keys at abutments, minor spalling and cracks at hinges, minor spalling at the column (damage requires no more than cosmetic repair) or minor cracking to the deck
- For tunnels, ds_2 is defined by minor cracking of the tunnel liner (damage requires no more than cosmetic repair) and some rock falling, or by slight settlement of the ground at a tunnel portal.

Moderate Damage (ds_3)

- For roadways, ds_3 is defined by moderate settlement (several inches) or offset of the ground.

- <u>For bridges</u>, ds_3 is defined by any column experiencing moderate (shear cracks) cracking and spalling (column structurally still sound), moderate movement of the abutment (<2"), extensive cracking and spalling of shear keys, any connection having cracked shear keys or bent bolts, keeper bar failure without unseating, rocker bearing failure or moderate settlement of the approach.

- <u>For tunnels</u>, ds_3 is defined by moderate cracking of the tunnel liner and rock falling.

<u>Extensive Damage</u> (ds_4)

- <u>For roadways</u>, ds_4 is defined by major settlement of the ground (few feet).

- <u>For bridges</u>, ds_4 is defined by any column degrading without collapse – shear failure - (column structurally unsafe), significant residual movement at connections, or major settlement approach, vertical offset of the abutment, differential settlement at connections, shear key failure at abutments.

- <u>For tunnels</u>, ds_4 is characterized by major ground settlement at a tunnel portal and extensive cracking of the tunnel liner.

<u>Complete Damage</u> (ds_5)

- <u>For roadways</u>, ds_5 is defined by major settlement of the ground (i.e., same as ds_4).

- <u>For bridges</u>, ds_5 is defined by any column collapsing and connection losing all bearing support, which may lead to imminent deck collapse, tilting of substructure due to foundation failure.

- <u>For tunnels</u>, ds_5 is characterized by major cracking of the tunnel liner, which may include possible collapse.

7.1.7 Component Restoration Curves

Restoration curves are developed based on a best fit to ATC-13 data for the social function classifications of interest (SF 25a through SF 25e) consistent with damage states defined in the previous section (first four classes in ATC-13). Figure 7.1 shows restoration curves for urban and major roads, Figure 7.2 represents restoration curves for highway bridges, while Figure 7.3 shows restoration curves for highway tunnels. The smooth curves shown in these figures are normal curves characterized by a mean and a standard deviation. The parameters of these restoration curves are given in Tables 7.4 and 7.5. The former table gives means and standard deviations for each restoration curve (i.e., smooth continuous curve), while the second table gives approximate discrete functions for the restoration curves developed.

Table 7.4 Continuous Restoration Functions for Highways (after ATC-13, 1985)

Damage State	Roadways		Highway Bridges		Highway Tunnels	
	Mean (Days)	**σ** (days)	**Mean** (Days)	**σ** (days)	**Mean** (Days)	**σ** (days)
Slight/Minor	0.9	0.05	0.6	0.6	0.5	0.3
Moderate	2.2	1.8	2.5	2.7	2.4	2.0
Extensive	21	16	75.0	42.0	45.0	30.0
Complete			230.0	110.0	210.0	110.0

The values shown in Table 7.5 below represent distributions on functionality for each restoration period based on damage state immediately after the earthquake.

Table 7.5 Discrete Restoration Functions for Highways

Roadways

Restoration Period	Functional Percentage		
	Slight	**Moderate**	**Extensive/Complete**
1 day	90	25	10
3 days	100	65	14
7 days	100	100	20
30 days	100	100	70
90 days	100	100	100

Bridges

Restoration Period	Functional Percentage			
	Slight	**Moderate**	**Extensive**	**Complete**
1 day	70	30	2	0
3 days	100	60	5	2
7 days	100	95	6	2
30 days	100	100	15	4
90 days	100	100	65	10

Tunnels

Restoration Period	Functional Percentage			
	Slight	**Moderate**	**Extensive**	**Complete**
1 day	90	25	5	0
3 days	100	65	8	3
7 days	100	100	10	3
30 days	100	100	30	5
90 days	100	100	95	15

7.1.8 Development of Damage Functions

Fragility curves for highway system components are defined with respect to classification and ground motion parameter.

Damage functions for Roadways

Fragility curves for major roads and urban roads are shown in Figures 7.4. and 7.5, respectively. The medians and dispersions of these curves are presented in Table 7.6.

Table 7.6 Damage Algorithms for Roadways

Permanent Ground Deformation			
Components	**Damage State**	**Median (in)**	**β**
Major Road (Hrd1)	slight/minor	12	0.7
	moderate	24	0.7
	extensive/complete	60	0.7
Urban Roads (Hrd2)	slight/minor	6	0.7
	moderate	12	0.7
	extensive/complete	24	0.7

Damage Functions for Bridges

There are 28 primary bridge types for which all four damage states are identified and described. For other bridges, fragility curves of the 28 primary bridge types are adjusted to reflect the expected performance of a specific bridge which may be better or worse than the corresponding primary bridge type.

A total of 224 bridge damage functions are obtained, 112 due to ground shaking and 112 due to ground failure. For a complete description on the theoretical background of the damage functions, see ***Basoz and Mander (1999).*** This document is referenced at the end of this section and can be obtained from NIBS or FEMA.

Medians of these damage functions are given in Table 7.7. The dispersion is set to 0.6 for the ground shaking damage algorithm and 0.2 for the ground failure damage algorithm. Only incipient unseating and collapse (i.e., which correspond to extensive and complete damage states) are considered as possible types of damage due to ground failure. Initial damage to bearings (i.e., which would correspond to slight and/or moderate damage states) from ground failure is not considered.

Figures 7.6 and 7.7 show example fragility curves for major bridges.

Table 7.7 Damage Algorithms for Bridges

	Sa [1.0 sec in g's] for Damage Functions due to Ground Shaking				PGD [inches] for Damage Functions due to Ground Failure			
CLASS	Slight	Moderate	Extensive	Complete	Slight	Moderate	Extensive	Complete
HWB1	0.40	0.50	0.70	0.90	3.9	3.9	3.9	13.8
HWB2	0.60	0.90	1.10	1.70	3.9	3.9	3.9	13.8
HWB3	0.80	1.00	1.20	1.70	3.9	3.9	3.9	13.8
HWB4	0.80	1.00	1.20	1.70	3.9	3.9	3.9	13.8
HWB5	0.25	0.35	0.45	0.70	3.9	3.9	3.9	13.8
HWB6	0.30	0.50	0.60	0.90	3.9	3.9	3.9	13.8
HWB7	0.50	0.80	1.10	1.70	3.9	3.9	3.9	13.8
HWB8	0.35	0.45	0.55	0.80	3.9	3.9	3.9	13.8
HWB9	0.60	0.90	1.30	1.60	3.9	3.9	3.9	13.8
HWB10	0.60	0.90	1.10	1.50	3.9	3.9	3.9	13.8
HWB11	0.90	0.90	1.10	1.50	3.9	3.9	3.9	13.8
HWB12	0.25	0.35	0.45	0.70	3.9	3.9	3.9	13.8
HWB13	0.30	0.50	0.60	0.90	3.9	3.9	3.9	13.8
HWB14	0.50	0.80	1.10	1.70	3.9	3.9	3.9	13.8
HWB15	0.75	0.75	0.75	1.10	3.9	3.9	3.9	13.8
HWB16	0.90	0.90	1.10	1.50	3.9	3.9	3.9	13.8
HWB17	0.25	0.35	0.45	0.70	3.9	3.9	3.9	13.8
HWB18	0.30	0.50	0.60	0.90	3.9	3.9	3.9	13.8
HWB19	0.50	0.80	1.10	1.70	3.9	3.9	3.9	13.8
HWB20	0.35	0.45	0.55	0.80	3.9	3.9	3.9	13.8
HWB21	0.60	0.90	1.30	1.60	3.9	3.9	3.9	13.8
HWB22	0.60	0.90	1.10	1.50	3.9	3.9	3.9	13.8
HWB23	0.90	0.90	1.10	1.50	3.9	3.9	3.9	13.8
HWB24	0.25	0.35	0.45	0.70	3.9	3.9	3.9	13.8
HWB25	0.30	0.50	0.60	0.90	3.9	3.9	3.9	13.8
HWB26	0.75	0.75	0.75	1.10	3.9	3.9	3.9	13.8
HWB27	0.75	0.75	0.75	1.10	3.9	3.9	3.9	13.8
HWB28	0.80	1.00	1.20	1.70	3.9	3.9	3.9	13.8

The damage algorithm for bridges can be broken into eight steps:

Step 1:
Get the bridge location (longitude and latitude), class (HWB1 through HWB28), number of spans (N), skew angle (α), span width (W), bridge length (L), and maximum span length (L_{max}). Note that the skew angle is defined as the angle between the centerline of a pier and a line normal to the roadway centerline.

Step 2:
Evaluate the soil-amplified shaking at the bridge site. That is, get the peak ground acceleration (PGA), spectral accelerations (Sa[0.3 sec] and Sa[1.0 sec]) and the permanent ground deformation (PGD).

Step 3:
Evaluate the following three modification factors:

$$K_{skew} = \mathrm{sqrt}[\sin(90-\alpha)]$$

$$K_{shape} = 2.5 \times Sa(1.0 \text{ sec}) / Sa(0.3 \text{ sec})$$

$K_{3D} = 1 + A / (N - B)$ A and B are read from Table 7.3

Step 4:
Modify the ground shaking medians for the "standard" fragility curves in Table 7.7 as follows:

New Median [for slight] = Old Median [for slight] x $Factor_{slight}$

Where
$Factor_{slight} = 1$ if $I_{shape} = 0$ (I_{shape} is read from Table 7.2)
or
$Factor_{slight}$ = minimum of (1, K_{shape}) if $I_{shape} = 1$

New median [moderate] = Old median [for moderate] * (K_{skew}) * (K_{3D})

New median [extensive] = Old median [for extensive] * (K_{skew}) * (K_{3D})

New median [complete] = Old median [for complete] * (K_{skew}) * (K_{3D})

Step 5:
Use the new medians along with the dispersion $\beta = 0.6$ to evaluate the ground shaking-related damage state probabilities. Note that Sa(1.0 sec) (listed in Table 7.7) is the parameter to use in this evaluation.

Step 6:
Modify the PGD medians for the "standard" fragility curves listed in Table 7.7 as follows:

New PGD median [for slight] = 'Table7.7' PGD median [for slight] x f_1
New PGD median [moderate] = 'Table7.7' PGD median [for moderate] x f_1
New PGD median [extensive] = 'Table7.7' PGD median [for extensive] x f_1
New PGD median [complete] = 'Table7.7' median [for complete] x f_2

Where f_1 and f_2 are modification factors that are functions of the number of spans (N), width of the span (W), length of the bridge (L), and the skewness (α) and can be computed using the equations in Table 7.8 below.

Table 7.8 Modifiers for PGD Medians

CLASS	f_1	f_2
HWB1	1	1
HWB2	1	1
HWB3	1	1
HWB4	1	1
HWB5	0.5 * L / [N . W . sin (α)]	0.5 * L / [N . W . sin (α)]
HWB6	0.5 * L / [N . W . sin (α)]	0.5 * L / [N . W . sin (α)]
HWB7	0.5 * L / [N . W . sin (α)]	0.5 * L / [N . W . sin (α)]
HWB8	1	sin (α)
HWB9	1	sin (α)
HWB10	1	sin (α)
HWB11	1	sin (α)
HWB12	0.5 * L / [N . W . sin (α)]	0.5 * L / [N . W . sin (α)]
HWB13	0.5 * L / [N . W . sin (α)]	0.5 * L / [N . W . sin (α)]
HWB14	0.5 * L / [N . W . sin (α)]	0.5 * L / [N . W . sin (α)]
HWB15	1	sin (α)
HWB16	1	sin (α)
HWB17	0.5 * L / [N . W . sin (α)]	0.5 * L / [N . W . sin (α)]
HWB18	0.5 * L / [N . W . sin (α)]	0.5 * L / [N . W . sin (α)]
HWB19	0.5 * L / [N . W . sin (α)]	0.5 * L / [N . W . sin (α)]
HWB20	1	sin (α)
HWB21	1	sin (α)
HWB22	0.5 * L / [N . W . sin (α)]	0.5 * L / [N . W . sin (α)]
HWB23	0.5 * L / [N . W . sin (α)]	0.5 * L / [N . W . sin (α)]
HWB24	0.5 * L / [N . W . sin (α)]	0.5 * L / [N . W . sin (α)]
HWB25	0.5 * L / [N . W . sin (α)]	0.5 * L / [N . W . sin (α)]
HWB26	1	sin (α)
HWB27	1	sin (α)
HWB28	1	1

Step 7:
Use the new medians along with the dispersion β = 0.2 to evaluate ground failure-related damage state probabilities.

Step 8:
Combine the damage state probabilities and evaluate functionality of bridge.

Example of bridge damage evaluation:
Consider a three-span simply supported prestressed concrete bridge seated on neoprene bearings located in the Memphis area. The table below lists the data for this bridge obtained from NBI. For the scenario earthquake, assume that the ground motion for rock conditions (NEHRP class B) is defined by the following parameters:

Sa(0.3 sec) = 2.1g, Sa(1.0 sec) = 0.24g PGA = 0.38g

Also, assume that the bridge is located in soil type D.

The median spectral acceleration ordinates for different damage states are determined as follows:

Step 1: Ground motion data is amplified for soil conditions (Table 4.10 in Chapter 4):

Sa(0.3 sec) = 2.1g (1 x 2.1g),
Sa(1.0 sec) = 0.43g (1.8 x 0.24g)
PGA = 0.53g (1.4 x 0.38g)

Step 2: The bridge class is determined.

Bridge Data Required for the Analysis

NBI field	Data	Remarks
27	1968	Year built
34	32	Angle of skew
43	501	Prestressed concrete, simple span
45	3	Number of spans
48	23	Maximum span length (m)
49	56	Total bridge length (m)

Based on the information in the table above, **HWB17** is determined to be the bridge class.

Step 3: Parameters needed in evaluating the median spectral accelerations are computed:

K_{skew} = sqrt[sin(90-α)] =sqrt [sin (90 – 32)] = 0.91

K_{shape} = 2.5 x Sa(1.0 sec) / Sa(0.3 sec) = 0.50

K_{3D} = 1 + A / (N – B) = 1 + 0.25 / (3-1) = 1.125 (See Tables 7.2 and 7.3)

Step 4:

From Table 7.2, I_{shape} is 0 for HWB17, therefore "long periods" governs, and $Factor_{slight}$ is 1. Therefore:

New Sa[1.0 sec] [for slight] = Old Sa[1.0 sec] [for slight] *$Factor_{slight}$
= 0.25g * 1.00 = 0.25g
New Sa[1.0 sec] [moderate] = Old Sa[1.0 sec] [for moderate] * (K_{skew}) * (K_{3D})
= 0.35g * 0.91 * 1.125 = 0.36g
New Sa[1.0 sec] [extensive] = Old Sa[1.0 sec] [for extensive] * (K_{skew}) * (K_{3D})
= 0.45g * 0.91 * 1.125 = 0.46g
New Sa[1.0 sec] [complete] = Old Sa[1.0 sec] [for complete] * (K_{skew}) * (K_{3D})
= 0.70g * 0.91 * 1.125 = 0.72g

Step 5:
With these new medians, the shaking-related discrete damage state probabilities are (using lognormal functions with the above medians and with betas equal to 0.6):

P[No damage] = 1 – 0.82 = 0.18
P[Slight damage] = 0.82 – 0.62 = 0.20
P[Moderate damage] = 0.62 – 0.46 = 0.16
P[Extensive damage] = 0.46 – 0.20 = 0.26
P[Complete damage] = 0.20

Damage Functions for Tunnels

The tunnel damage functions developed based on the damage potential of their subcomponents, namely the liner and the portal (G&E, 1994). G&E findings are based partly on earthquake experience data reported by Dowding et. al. (1978) and Owen et. al (1981). The subcomponent damage functions are given in Tables A.7.1 and A.7.2.

Ten tunnel damage functions were developed, four damage functions for ground shaking (PGA) and six damage functions for ground failure (PGD). Medians and dispersion factors of these damage functions are given in Table 7.9. Graphical representations of these damage functions are also provided. Figures 7.8 and Figure 7.9 plot fragility curves due to PGA for bored/drilled and cut & cover tunnels, respectively, while Figure 7.10 presents fragility curves for tunnels due to PGD.

Table 7.9 Damage Algorithms for Tunnels

Peak Ground Acceleration			
Classification	**Damage State**	**Median (g)**	**β**
Bored/Drilled (HTU1)	slight/minor moderate	0.6 0.8	0.6 0.6
Cut & Cover (HTU2)	slight/minor moderate	0.5 0.7	0.6 0.6
Permanent Ground Deformation			
Classification	**Damage State**	**Median (in)**	**β**
Bored/Drilled (HTU1)	slight/moderate extensive complete	6.0 12.0 60.0	0.7 0.5 0.5
Cut & Cover (HTU2)	slight/moderate extensive complete	6.0 12.0 60.0	0.7 0.5 0.5

7.1.9 Guidance for Loss Estimation Using Advanced Data and Models Analysis

For an advanced analysis, experts can use the methodology developed with the flexibility to (1) include a more refined inventory of the transportation system pertaining to the study area, and (2) include component-specific and system-specific fragility data. User-supplied damage algorithms can be modified to incorporate improved information about key components of the highway system. Similarly, improved restoration curves can be developed, given knowledge of available resources and a more accurate layout of the transportation network within the local topographic (i.e., if the redundancy and importance of highway components of the network are known).

7.1.10 References

(1) Applied Technology Council, "Earthquake Damage Evaluation Data for California", ATC-13, Redwood City, CA, 1985.

(2) Dowding, C.H. and Rozen, A., "Damage to Rock Tunnels from Earthquake Shaking", *Journal of the Geotechnical Engineering Division*, American Society of Civil Engineers, New York, NY, February 1978.

(3) National Institute of Building Sciences, “Enhancement of the Highway Transportation Lifeline Module in Hazus”, prepared by Nesrin Basoz and John Mander, January 1999.

(4) Kim, S.H., "A GIS-Based Regional Risk Analysis Approach for Bridges against Natural Hazards", a dissertation submitted to the faculty of the graduate school of the State University of New York at Buffalo, September 1993.

(5) Owen, G.N. and Scholl, R.E., "Earthquake Engineering Analysis of a Large Underground Structures", Federal Highway Administration and National Science Foundation, FHWA/RD-80/195, January 1981.

(6) G&E Engineering Systems, Inc. (G&E), "NIBS Earthquake Loss Estimation Methods, Technical Manual, Transportation Systems (Highway Systems)", May 1994.

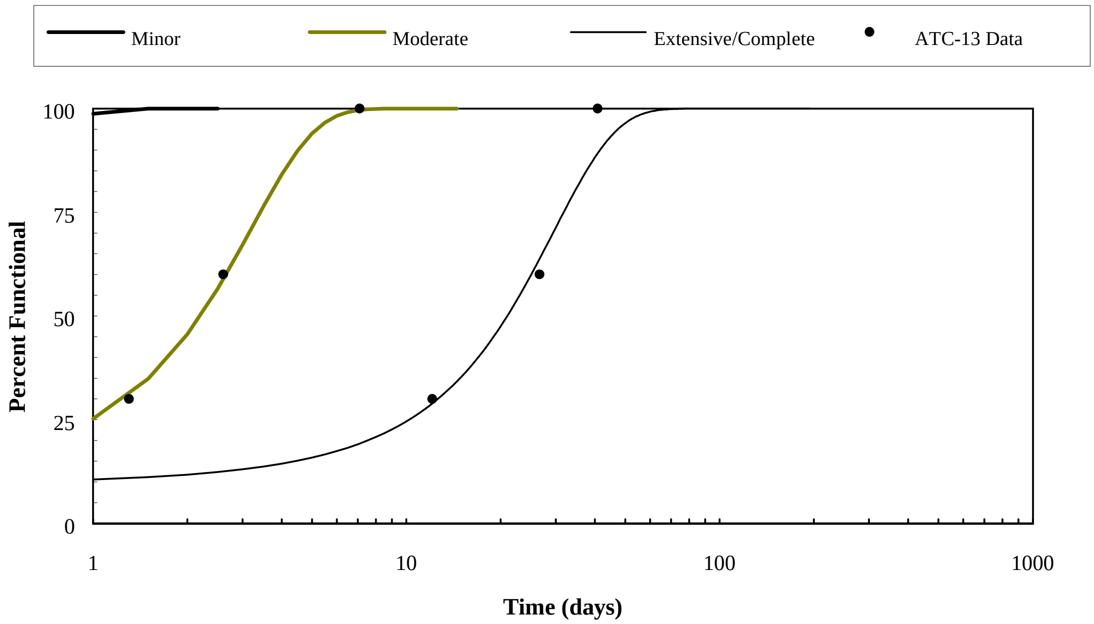


Figure 7.1 Restoration Curves for Urban and Major Roads (after ATC-13, 1985).

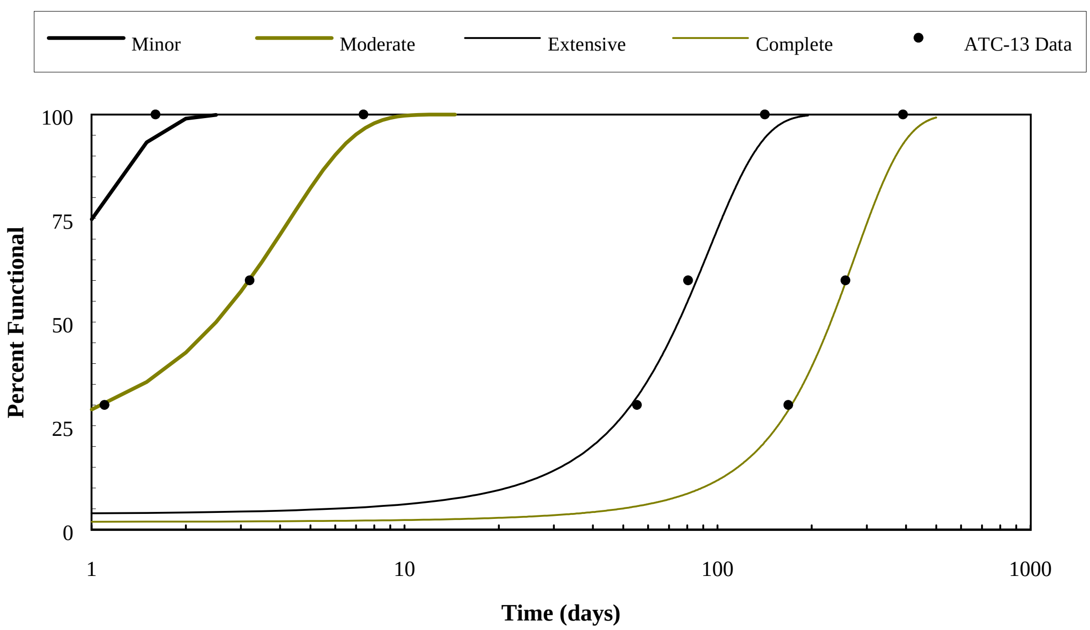


Figure 7.2 Restoration Curves for Highway Bridges (after ATC-13, 1985).

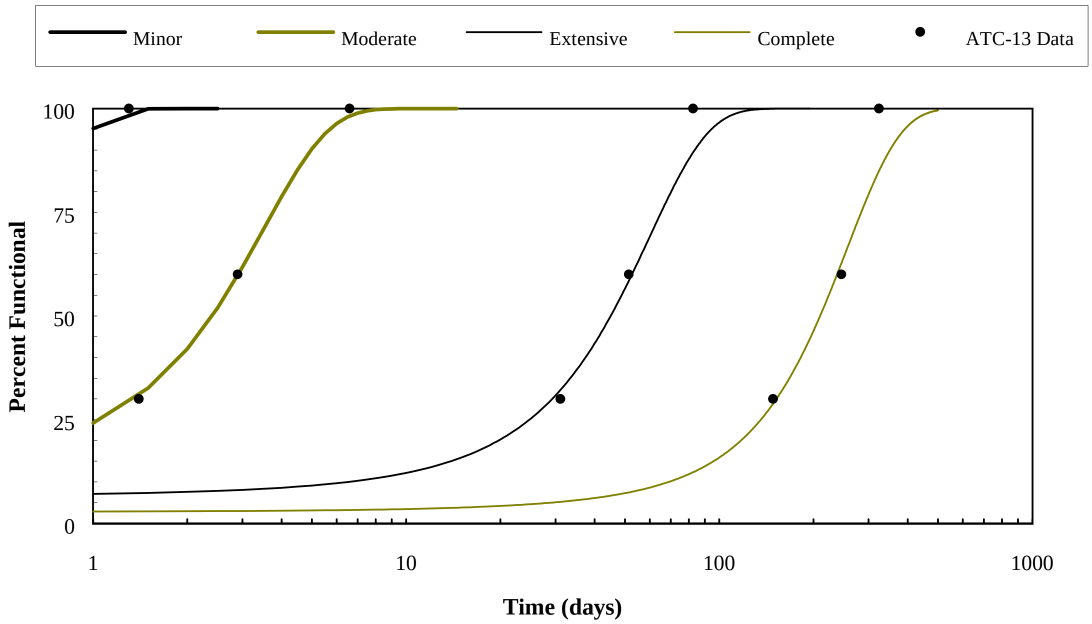


Figure 7.3 Restoration Curves for Highway Tunnels (after ATC-13, 1985).

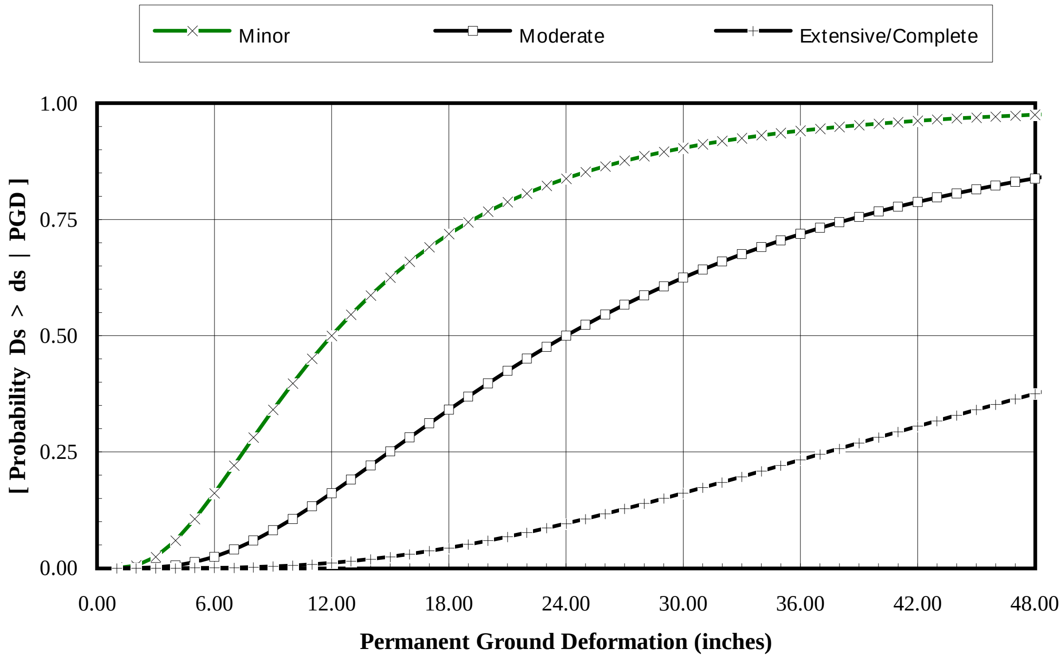


Figure 7.4 Fragility Curves at Various Damage States for Interstate and State Highways.

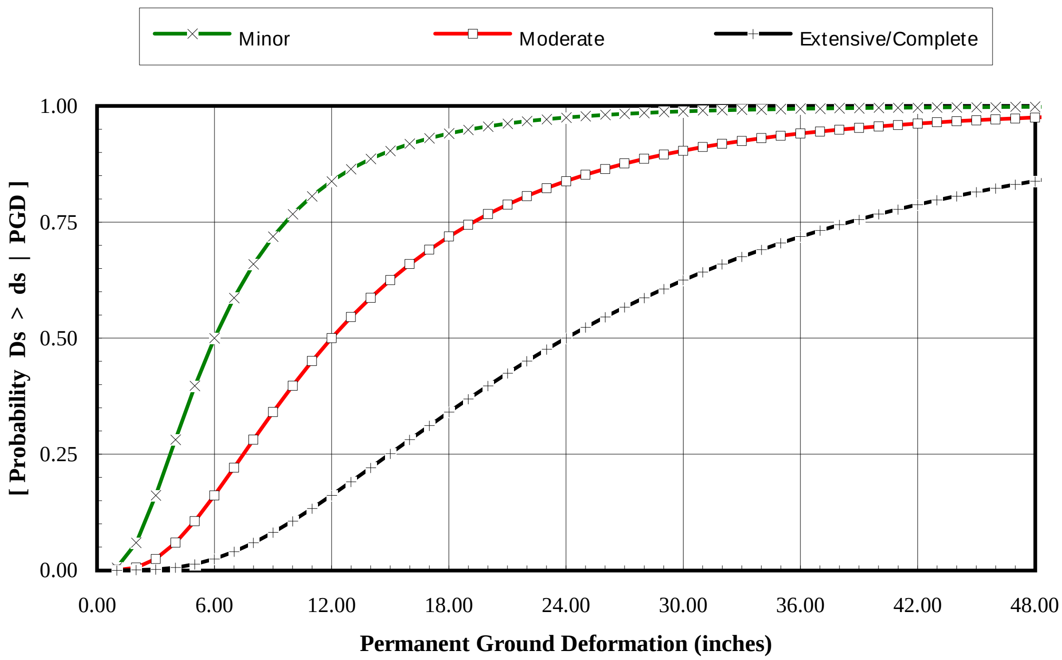


Figure 7.5 Fragility Curves at Various Damage States for Urban roads.

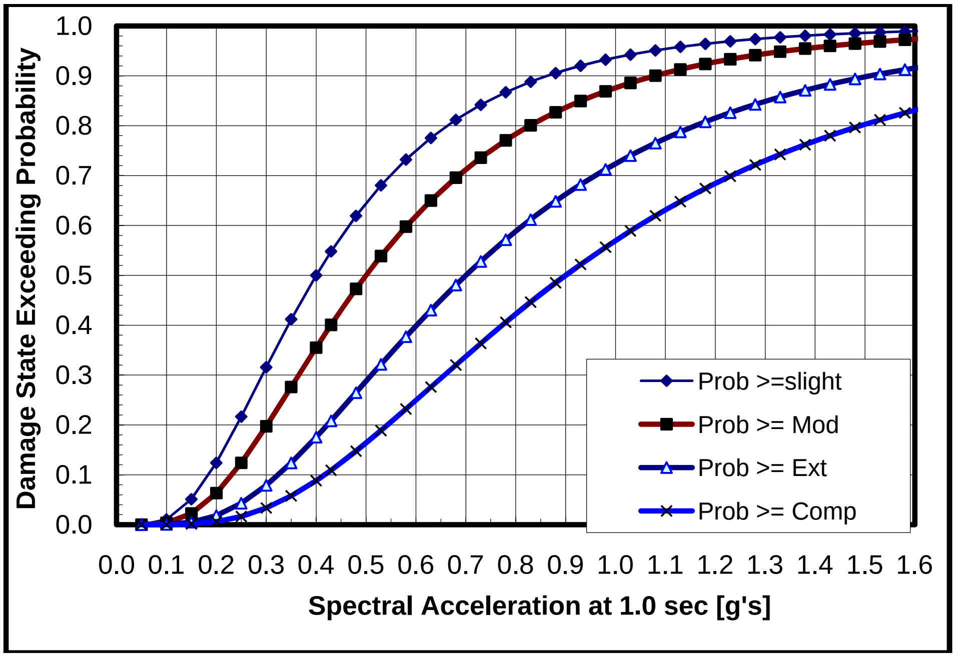


Figure 7.6 Fragility Curves for Conventially Designed Major Bridges (HWB1).

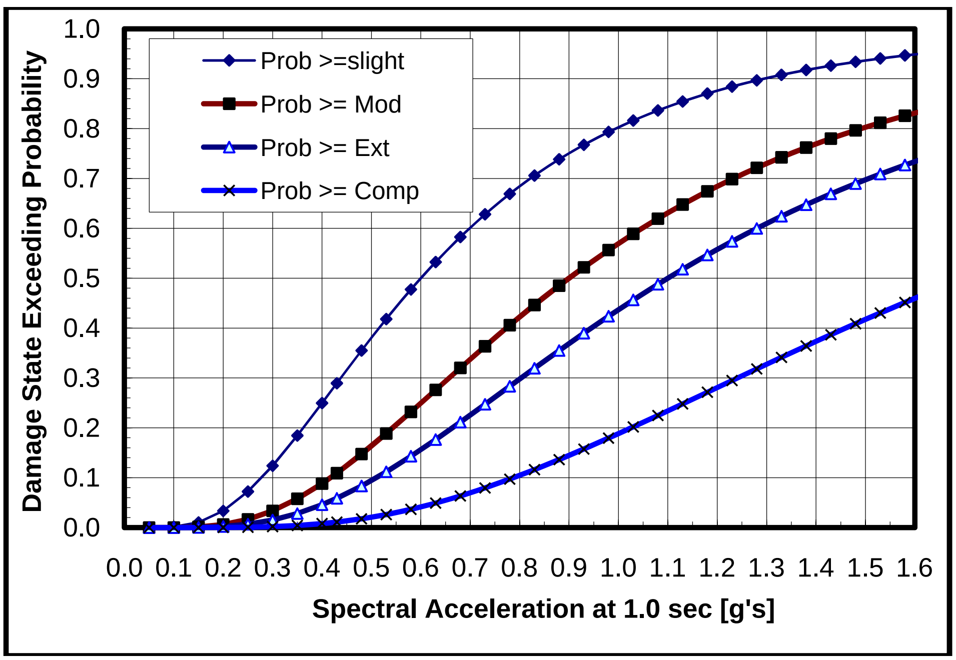


Figure 7.7 Fragility Curves for Seismically Designed Major Bridges (HWB2).

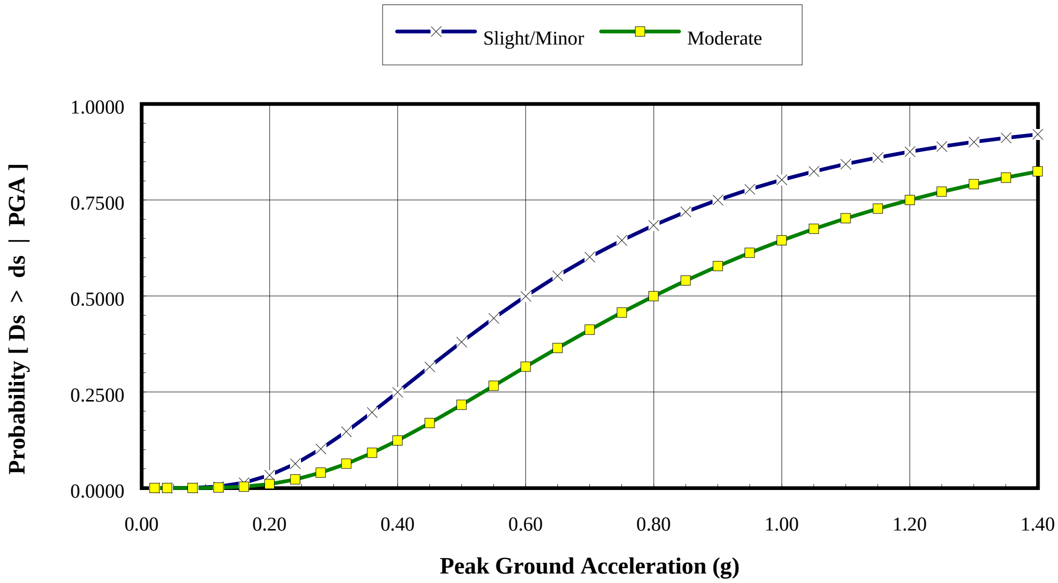


Figure 7.8 Fragility Curves at Various Damage States for Bored/Drilled Tunnels Subject to Peak Ground Acceleration.

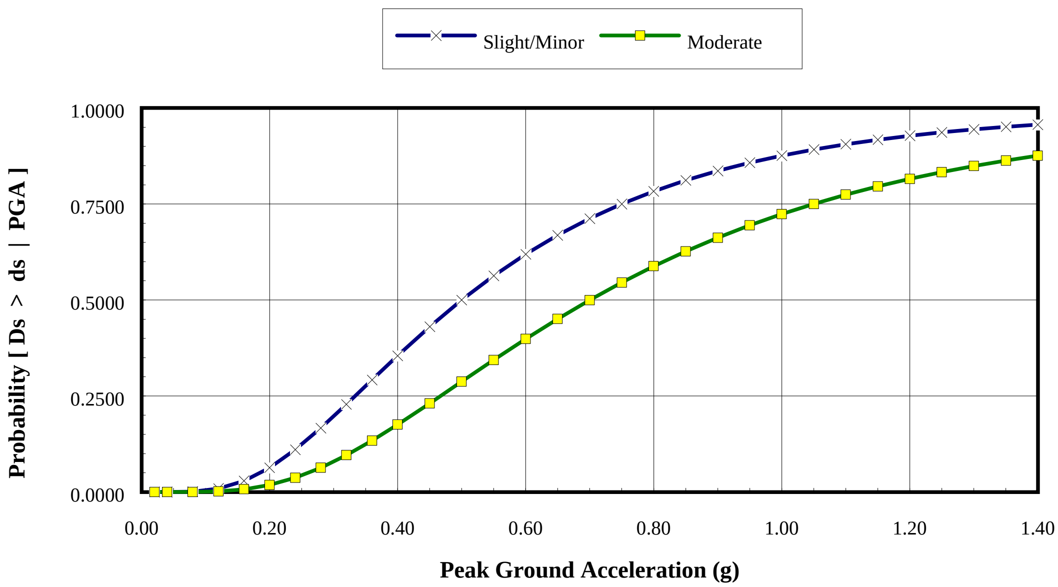


Figure 7.9 Fragility Curves at Various Damage States for Cut & Cover Tunnels Subject to Peak Ground Acceleration.

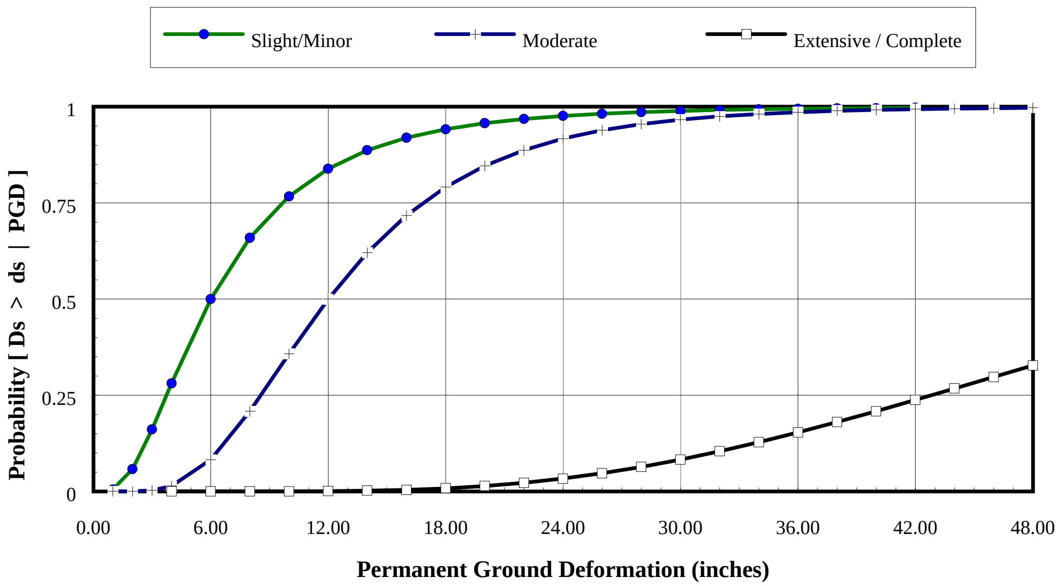


Figure 7.10 Fragility Curves at Various Damage States for All Types of Tunnels Subject to Permanent Ground deformation.

7.2 Railway Transportation System

7.2.1 Introduction

This section presents an earthquake loss estimation methodology for a railway transportation system. This system consists of tracks/roadbeds, bridges, tunnels, urban stations, maintenance facilities, fuel facilities, and dispatch facilities. Past earthquake damage reveals that bridges, tunnels, urban stations, maintenance facilities, fuel facilities, and dispatch facilities are vulnerable to both ground shaking and ground failure, while railway tracks/roadbeds are significantly affected by ground failure alone. Railway tracks located on soft soil or fill or which cross a surface fault rupture can experience failure resulting in loss of functionality. Railway bridges that fail usually result in significant disruption to the transportation network, especially bridges that cross waterways. Likewise, railway tunnels are often not redundant, and major disruption to the transportation system is likely to occur should a tunnel become non-functional.

7.2.2 Scope

The scope of this section includes development of methods for estimation of earthquake damage to a railway transportation system given knowledge of the system's components (i.e., tracks, bridges, tunnels, stations, maintenance facilities, fuel facilities, or dispatch facilities), the classification of each component (e.g., for fuel facilities, whether the equipment within the facility is anchored or not), and the ground motion (i.e. peak ground acceleration and permanent ground deformation).

Damage states describing the level of damage to each railway system component are defined (i.e. slight/minor, moderate, extensive or complete). Damage states are related to damage ratio (defined as ratio of repair to replacement cost) for evaluation of direct economic loss. Component restoration curves are provided for each damage state to evaluate loss of function. Restoration curves describe the fraction or percentage of the component that is expected to be open or operational as a function of time following the earthquake. For example, an extensively damaged railway facility might be closed (0% functional) immediately following the earthquake, but 100% functional after 30 days.

Fragility curves are developed for each type of railway system component. These curves describe the probability of reaching or exceeding each damage state given the level of ground motion.

Evaluation of component functionality is done similar to the way it was done for highway components.

Interdependence of components on the overall system functionality is not addressed by the methodology. Such considerations require a system (network) analysis.

7.2.3 Input Requirements and Output Information

Required input to estimate damage to railway systems includes the following items:

Track and Roadbeds

- Geographical location of railway links [longitude and latitude of end nodes]
- Permanent ground deformation (PGD) at trackbed link

Railway Bridges

- Geographical location of bridge (longitude and latitude)
- Spectral Acceleration at 0.3 and 1.0 seconds and PGD at bridge
- Bridge classification

Railway Tunnels

- Geographical location of tunnels (longitude and latitude)
- PGA and PGD at tunnel
- Tunnel classification

Railway System Facilities

- Geographical location of facilities (longitude and latitude)
- PGA and PGD at facility
- Facility classification

Direct damage output for railway systems includes probability estimates of (1) component functionality and (2) physical damage, expressed in terms of the component's damage ratio. Damage ratios, used as inputs to the direct economic loss module, are presented in section 15.3 of Chapter 15.

Component functionality is described similar to highway system components, that is, by the probability of being in a damage state (immediately following the earthquake) and by the associated fraction or percentage of the component that is expected to be functional after a specified period of time.

7.2.4 Form of Damage Functions

Damage functions or fragility curves for all railway system components described below are modeled as lognormal functions that give the probability of reaching or exceeding different levels of damage for a given level of ground motion. Each fragility curve is characterized by a median value of ground motion (or failure) and an associated dispersion factor (lognormal standard deviation). Ground motion is quantified in terms of peak ground acceleration (PGA) and ground failure is quantified in terms of permanent ground displacement (PGD).

- For tracks/roadbeds, fragility curves are defined in terms of PGD.
- For railway bridges, fragility curves are defined similar to those for highway bridges
- For tunnels, fragility curves are the same as defined for highway systems (in terms of PGA and PGD)
- For railway system facilities, fragility curves are defined in terms of PGA or Sd and PGD.

Definitions of various damage states and the methodology used in deriving all these fragility curves are presented in the following sections.

7.2.5 Description of Railway System Components

A railway system consists of four components: tracks/roadbeds, bridges, tunnels, and facilities. This section provides a brief description of each.

Tracks/Roadbeds

Tracks/roadbeds refers to the assembly of rails, ties, and fastenings, and the ground on which they rest. Only one classification is adopted for these components. This classification is analogous to that of urban roads in highway systems.

Bridges

Railway bridges are classified similar to highway steel and concrete bridges.

Tunnels

Railway tunnels follow the same classification as highway tunnels. That is, they are classified either as bored/drilled tunnels, or cut & cover tunnels.

Railway System Facilities

Railway system facilities include urban and suburban stations, maintenance facilities, fuel facilities, and dispatch facilities.

Urban and Suburban stations: are generally key connecting hubs that are important for system functionality. In western US, these buildings are mostly made of reinforced concrete shear walls or moment resisting steel frames, while in the eastern US, the small stations are mostly wood and the large ones are mostly masonry or braced steel frames..

Maintenance facilities are housed in large structures that are not usually critical for system functionality as maintenance activities can be delayed or performed elsewhere. These building structures are often made of steel braced frames.

Fuel facilities include buildings, tanks (anchored, unanchored, or buried), backup power systems (if available, anchored or unanchored diesel generators), pumps, and other equipment (anchored or unanchored). It should be mentioned that anchored equipment in general refers to equipment designed with special seismic tiedowns or tiebacks, while unanchored equipment refers to equipment designed with no special considerations other than the manufacturer's normal requirements. While some vibrating components, such as pumps, are bolted down regardless of concern for earthquakes, as used here “anchored” means all components have been engineered to meet seismic criteria which may include bracing (e.g., pipe or stack bracing) or flexibility requirements (e.g., flexible connections across separation joints) as well as anchorage. These definitions of anchored and unanchored apply to all lifeline components. The fuel facility functionality is determined with a fault tree analysis considering redundancies and subcomponent behavior. Note that generic building damage functions are used in this fault tree analysis for developing the overall fragility curve of fuel facilities. Above ground tanks are typically made of steel with roofs also made of steel. Buried tanks are typically concrete wall construction with concrete roofs. In total, five types of fuel facilities are considered. These are: fuel facilities with or without anchored equipment and with or without backup power (all combinations), and fuel facilities with buried tanks.

Dispatch facilities consist of buildings, backup power supplies (if available, anchored or unanchored diesel generators), and electrical equipment (anchored or unanchored). Generic reinforced concrete building with shear walls damage functions, are used in this fault tree analysis for developing the overall fragility curves for dispatch facilities. In total, four types of dispatch facilities are considered. These are dispatch facilities with or without anchored equipment and with or without backup power (all combinations).

7.2.6 Definitions of Damage States

A total of five damage states are defined for railway system components. These are none (ds_1), slight/minor (ds_2), moderate (ds_3), extensive (ds_4) and complete (ds_5).

Slight/Minor Damage (ds_2)

- For tracks and roadbeds, ds_2 is defined by minor (localized) derailment due to slight differential settlement of embankment or offset of the ground.
- For railway bridges, ds_2 is defined similar to highway bridges.
- For railway tunnels, ds_2 is defined similar to highway tunnels.
- For railway system facilities,

◊ for urban stations and maintenance facilities, ds_2 is defined by slight building damage (check building module for full description of potential damage).

◊ for fuel facilities with anchored equipment, ds_2 is defined by slight damage to pump building, minor damage to anchor of tanks, or loss of off-site power (check electric power systems for more on this) for a very short period and minor damage to backup power (i.e. to diesel generators, if available).

◊ for fuel facilities with unanchored equipment, ds_2 is defined by elephant foot buckling of tanks with no leakage or loss of contents, slight damage to pump building, or loss of commercial power for a very short period and minor damage to backup power (i.e to diesel generators, if available).

◊ for fuel facilities with buried tanks (PGD related damage), ds_2 is defined by minor uplift (few inches) of the buried tanks or minor cracking of concrete walls.

◊ for dispatch facilities with anchored equipment, ds_2 is defined by minor anchor damage, slight damage to building, or loss of commercial power for a very short period and minor damage to backup power (i.e. diesel generators, if available).

◊ for dispatch facilities with unanchored equipment, ds_2 is defined by loss of off-site power for a very short period and minor damage to backup power (i.e. to diesel generators, if available), or slight damage to building.

Moderate Damage (ds_3)

- For railway tracks and roadbeds, ds_3 is defined by considerable derailment due to differential settlement or offset of the ground. Rail repair is required.
- For railway bridges, ds_3 is defined as for highway bridges.
- For railway tunnels, ds_3 is defined as for highway tunnels
- For railway system facilities,

◊ for urban stations and maintenance facilities, ds_3 is defined by moderate building damage (check building module for description of potential damage).

◊ for fuel facilities with anchored equipment, ds_3 is defined by elephant foot buckling of tanks with no leakage or loss of contents, considerable damage to equipment, moderate damage to pump building, or loss of commercial power for few days and malfunction of backup power (i.e., diesel generators, if available).

◊ for fuel facilities with unanchored equipment, ds_3 is defined by elephant foot buckling of tanks with partial loss of contents, moderate damage to pump building, loss of commercial power for few days and malfunction of backup power (i.e., diesel generators, if available).

◊ for fuel facilities with buried tanks, ds_3 is defined by damage to roof supporting columns, and considerable cracking of walls.

◊ for dispatch facilities with anchored equipment, ds_3 is defined by considerable anchor damage, moderate damage to building, or loss of commercial power for few days and malfunction of backup power (i.e., diesel generators, if available).

◊ for dispatch facilities with unanchored equipment, ds_3 is defined by moderate damage to building, or loss of off-site power for few days and malfunction of backup power (i.e., diesel generators, if available)..

Extensive Damage (ds_4)

- For railway tracks/roadbeds, ds_4 is defined by major differential settlement of the ground resulting in potential derailment over extended length.
- For railway bridges, ds_4 is defined as for highway bridges.
- For railway tunnels, ds_4 is defined as for highway tunnels.
- For railway system facilities,

◊ for urban stations and maintenance facilities, ds_4 is defined by extensive building damage (check building module for description of potential damage).

◊ for fuel facilities with anchored equipment, ds_4 is defined by elephant foot buckling of tanks with loss of contents, extensive damage to pumps (cracked/sheared shafts), or extensive damage to pump building.

◊ for fuel facilities with unanchored equipment, ds_4 is defined by weld failure at base of tank with loss of contents, extensive damage to pump building, or extensive damage to pumps (cracked/sheared shafts).

◊ for fuel facilities with buried tanks, ds_4 is defined by considerable uplift (more than a foot) of the tanks and rupture of the attached piping.

◊ For dispatch facilities with unanchored or anchored equipment, ds_4 is defined by extensive building damage.

<u>Complete Damage</u> (ds_5)

- <u>For railway tracks/roadbeds</u>, ds_5 is the same as ds_4.
- <u>For railway bridges</u>, ds_5 is defined as for highway bridges.
- <u>For railway tunnels</u>, ds_5 is defined as for highway tunnels.
- <u>For railway system facilities</u>,

  ◊ For urban stations and maintenance facilities, ds_5 is defined by extensive to complete building damage (check building module for description of potential damage).

  ◊ For fuel facilities with anchored equipment, ds_5 is defined by weld failure at base of tank with loss of contents, or extensive to complete damage to pump building.

  ◊ For fuel facilities with unanchored equipment, ds_5 is defined by tearing of tank wall or implosion of tank (with total loss of content), or extensive/complete damage to pump building.

  ◊ For fuel facilities with buried tanks, ds_5 is same as ds_4.

  ◊ For dispatch facilities with unanchored or anchored equipment, ds_5 is defined by complete damage to building.

7.2.7 Component Restoration Curves

Restoration curves are developed based in part on ATC-13 damage data for the social function classifications of interest (SF 26a through SF 26d) consistent with damage states defined in the previous section. Normally distributed functions are used to approximate these restoration curves, as was done for highway systems. Means and dispersions (standard deviations) of these restoration functions are given in Table 7.10.a. Table 7.10.b gives approximate discrete functions for these developed restoration functions. Figures 7.11 through 7.14 show restoration functions for railway tracks/roadbed, bridges, tunnels and facilities, respectively. ATC-13 restoration data for railway terminal stations are used to generically represent all other railway facilities.

Table 7.10.a Continuous Restoration Functions for Railway System Components (after ATC-13, 1985)

Classification	Damage State	Mean (Days)	σ (days)
Railway Tracks	slight/minor	0.9	0.07
	moderate	3.3	3.0
	extensive	15.0	13.0
	complete	65.0	45.0
Railway Bridges	slight/minor	0.9	0.06
	moderate	2.8	1.8
	extensive	31.0	22.0
	complete	110.0	73.0
Railway Tunnels	slight/minor	0.9	0.05
	moderate	4.0	3.0
	extensive	37.0	30.0
	complete	150.0	80.0
Railway Facilities	slight/minor	0.9	0.05
	moderate	1.5	1.5
	extensive	15.0	15.0
	complete	65.0	50.0

Table 7.10.b Discretized Restoration Functions for Railway System Components

Classification	Damage State	1 day	3 days	7 days	30 days	90 days
		Functional Percentage				
Railway Tracks	slight/minor	90	100	100	100	100
	moderate	22	46	90	100	100
	extensive	14	18	28	87	100
	complete	6	8	10	22	70
Railway Bridges	slight/minor	80	100	100	100	100
	moderate	15	55	100	100	100
	extensive	9	10	14	50	100
	complete	7	7	8	14	40
Railway Tunnels	slight/minor	95	100	100	100	100
	moderate	16	38	85	100	100
	extensive	11	13	16	40	97
	complete	3	4	4	7	22
Railway Facilities	slight/minor	95	100	100	100	100
	moderate	37	85	100	100	100
	extensive	15	20	29	83	100
	complete	10	11	12	25	70

7.2.8 Development of Damage Functions

Fragility curves for railway system components are defined with respect to classification and ground motion parameter.

Damage functions for Railway Tracks/Roadbeds

Damage functions for tracks/roadbeds are similar to those of major roads. The medians and dispersions of these curves were given in Table 7.6 (see highway system section).

Damage Functions for Railway Bridges

Fragility curves for bridges are the same ones presented in section 7.1.8 for highway bridges.

Damage Functions for Tunnels

Tunnel damage functions are the same as those derived for highways. These were given in Table 7.9 and plotted in Figures 7.9 and 7.10 of the "highway systems" section.

Damage Functions for Railway System Facilities

Damage functions for railway system facilities are defined in terms of spectral values and PGD. Note that, unless it is specified otherwise, ground failure (PGD) related damage functions for these facilities are assumed to be similar to those described for buildings. These are:

- For lateral spreading, a lognormal damage function with a median of 60 inches and a dispersion of 1.2 is assumed for the damage state of "at least extensive". 20% of this damage is assumed to be complete. That is, for a PGD of 10" due to lateral spreading, there is a 7% probability of "at least extensive" damage.

- For vertical settlement, a lognormal curve with a median of 10 inches and a dispersion of 1.2 is assumed for the damage state of "at least extensive". 20% of this damage is assumed to be complete. That is, for a PGD of 10" due to vertical settlement, there is a 50% chance of "at least extensive" damage.

- For fault movement or landslide, a lognormal curve with a median of 10 inches and a dispersion of 0.5 is assumed for "complete" damage state. That is, for 10 inches of PGD due to fault movement or landslide, there is a 50% chance of "complete" damage.

An example of how to combine multiple PGD algorithms with a PGA algorithm is presented later in this section.

Damage Functions for Urban Stations and Maintenance Facilities

These damage functions are similar to the building fragility curves developed in Chapter 5.

Damage Functions for Fuel Facilities

Fragility curves are developed for the five types of fuel facilities mentioned before, namely, fuel facilities with anchored equipment and backup power, fuel facilities with anchored equipment but no backup power, fuel facilities with unanchored equipment and backup power, fuel facilities with unanchored equipment and no backup power, and fuel facilities with buried tanks. Medians and dispersions of damage functions to fuel facility subcomponents are summarized in Tables B.7.3 and B.7.4 of Appendix 7B. A generic building type is used in developing fragility curves for fuel facilities in the specified fault tree logic (see Table B.7.3 of Appendix 7B). Note that the interaction effects, specifically that of the electric power module, are considered in this fault tree logic for the slight/minor and moderate damage states (refer to section 8.5.8 of Chapter 8 for more details on loss of commercial power effects on other lifelines).

Component fragility curves are obtained using the same methodology as used for bridges wherein a lognormal curve that best fits the results of the Boolean combination is determined numerically. It should be mentioned that the Boolean logic is implicitly presented within the definition of a particular damage state.

The fault tree shown in Figure 7.19a presents the Boolean logic for the case of moderate damage to fuel facilities with anchored equipment and backup power, while Figure 7.19b compares the fragility curve resulting from the Boolean combination to the fitted lognormal fragility curve. The dotted line in Figure 7.19 represents the overall fuel facility fragility curve.

The medians and dispersions of the damage functions for anchored and unanchored fuel facilities are shown in Table 7.11. These damage functions are also shown as fragility curves in Figures 7.20.a through 7.20e.

Table 7.11 Damage Algorithms for Fuel Facilities

Peak Ground Acceleration			
Classification	**Damage State**	**Median (g)**	**β**
Facility with Anchored Components w/ Backup Power	slight/minor moderate extensive complete	0.23 0.43 0.64 1.10	0.50 0.45 0.60 0.60
Facility with Anchored Components w/o Backup Power	slight/minor moderate extensive complete	0.12 0.27 0.64 1.10	0.55 0.50 0.60 0.60
Facility with Unnchored Components w/ Backup Power	slight/minor moderate extensive complete	0.10 0.23 0.48 0.80	0.55 0.50 0.60 0.60
Facility with Unnchored Components w/o Backup Power	slight/minor moderate extensive complete	0.09 0.20 0.48 0.80	0.50 0.45 0.60 0.60

Permanent Ground Deformation			
Classification	**Damage State**	**Median (in)**	**β**
Fuel facility w/ buried tanks	slight/minor moderate extensive/ Complete	4 8 24	0.5 0.5 0.5

PGA Related Damage Functions for Dispatch Facilities

As with fuel facilities, the same generic building type is used in developing the PGA related fragility curves for dispatch facilities in the fault tree logic. The medians and dispersions of the PGA related damage functions for anchored and unanchored dispatch facilities are given in Table 7.12 and plotted in Figures 7.21.c through 7.21.d. Note that the medians and dispersions of the damage functions for dispatch facility subcomponents are summarized in Tables B.7.5 and B.7.6 of Appendix 7B.

Table 7.12 Damage Algorithms for Dispatch Facilities

Peak Ground Acceleration			
Classification	**Damage State**	**Median (g)**	**β**
Facility with Anchored Components w/ Backup Power	slight/minor moderate extensive complete	0.15 0.35 0.8 1.50	0.75 0.65 0.80 0.80
Facility with Anchored Components w/o Backup Power	slight/minor moderate extensive complete	0.12 0.27 0.80 1.50	0.50 0.45 0.80 0.80
Facility with Unnchored Components w/ Backup Power	slight/minor moderate extensive complete	0.13 0.28 0.80 1.50	0.55 0.50 0.80 0.80
Facility with Unnchored Components w/o Backup Power	slight/minor moderate extensive complete	0.11 0.23 0.80 1.50	0.45 0.40 0.80 0.80

Note that the values of Table 7.12 indicate that the damage functions of dispatch facilities are mostly dominated by the building behavior.

Multiple Hazards Analysis for Railway System Facilities

In this section, a hypothetical example illustrating the methodology for combining multiple hazards for nodal facilities is presented.

Assume that due to some earthquake, a railway fuel facility with anchored components and backup power is subject to a PGA level of 0.3g, a lateral spreading displacement of 12 inches, a vertical settlement of 3 inches, and a potential landslide displacement of 15 inches. Assume also that the probability of liquefaction is 0.6, and that the probability of landslide is 0.7.

- Due to ground shaking, the following probabilities of exceedence are obtained:

$$P[\ D_s \geq ds_2 \mid PGA = 0.3g\ ] = 0.70$$
$$P[\ D_s \geq ds_3 \mid PGA = 0.3g\ ] = 0.21$$
$$P[\ D_s \geq ds_4 \mid PGA = 0.3g\ ] = 0.10$$
$$P[\ D_s \geq ds_5 \mid PGA = 0.3g\ ] = 0.02$$

- Due to vertical settlement, the following probabilities of exceedence are obtained:

$$P[\ D_s \geq ds_2 \mid PGD = 3 \text{ inches}\ ] = 0.16$$
$$P[\ D_s \geq ds_3 \mid PGD = 3 \text{ inches}\ ] = 0.16$$

$$P[\, D_s \geq ds_4 \mid PGD = 3 \text{ inches}] = 0.16$$
$$P[\, D_s \geq ds_5 \mid PGD = 3 \text{ inches} \,] = 20\% * 0.16 = 0.03$$

- Due to lateral spreading, the following probabilities of exceedence are obtained:

$$P[\, D_s \geq ds_2 \mid PGD = 12 \text{ inches} \,] = 0.09$$
$$P[\, D_s \geq ds_3 \mid PGD = 12 \text{ inches} \,] = 0.09$$
$$P[\, D_s \geq ds_4 \mid PGD = 12 \text{ inches}] = 0.09$$
$$P[\, D_s \geq ds_5 \mid PGD = 12 \text{ inches} \,] = 20\% * 0.09 = 0.02$$

Therefore, for liquefaction, <u>vertical settlement controls</u>

- Due to landslide, the following probabilities of exceedence are obtained:

$$P[\, D_s \geq ds_2 \mid PGD = 15 \text{ inches} \,] = 0.64$$
$$P[\, D_s \geq ds_3 \mid PGD = 15 \text{ inches} \,] = 0.64$$
$$P[\, D_s \geq ds_4 \mid PGD = 15 \text{ inches}] = 0.64$$
$$P[\, D_s \geq ds_5 \mid PGD = 15 \text{ inches} \,] = 0.64$$

Next, we compute the combined probabilities of exceedence (from complete to slight/minor):

$$\begin{aligned} P[\, D_s \geq ds_5 \,] &= 0.02 + 0.6x0.03 + 0.7x0.64 \\ &\quad - 0.02x0.6x0.03 - 0.02x0.7x0.64 - 0.6x0.03x0.7x0.64 \\ &\quad + 0.02x0.6x0.03x0.7x0.64 \\ &= 0.47 \end{aligned}$$

$$\begin{aligned} P[\, D_s \geq ds_4 \,] &= 0.10 + 0.6x0.16 + 0.7x0.64 \\ &\quad - 0.10x0.6x0.16 - 0.10x0.7x0.64 - 0.6x0.16x0.7x0.64 \\ &\quad + 0.10x0.6x0.16x0.7x0.64 \\ &= 0.55 \end{aligned}$$

$$\begin{aligned} P[\, D_s \geq ds_3 \,] &= 0.21 + 0.6x0.16 + 0.7x0.64 \\ &\quad - 0.21x0.6x0.16 - 0.21x0.7x0.64 - 0.6x0.16x0.7x0.64 \\ &\quad + 0.21x0.6x0.16x0.7x0.64 \\ &= 0.61 \end{aligned}$$

$$\begin{aligned} P[\, D_s \geq ds_2 \,] &= 0.70 + 0.6x0.16 + 0.7x0.64 \\ &\quad - 0.70x0.6x0.16 - 0.16x0.7x0.64 - 0.6x0.16x0.7x0.64 \\ &\quad + 0.70x0.6x0.16x0.7x0.64 \\ &= 0.85 \end{aligned}$$

Therefore, the <u>combined discrete damage states probabilities</u> are:

$$P[\, D_s = ds_1 \,] = 1 - 0.85 = 0.15$$
$$P[\, D_s = ds_2 \,] = 0.85 - 0.61 = 0.24$$

$P[\ D_s\ =\ ds_3\ ] = 0.61 - 0.55 = 0.06$
$P[\ D_s\ =\ ds_4\ ] = 0.55 - 0.47 = 0.08$
$P[\ D_s\ =\ ds_5\ ] = 0.47$

These discrete values will then be used in the evalution of functionality and economic losses.

7.2.9 Guidance for Loss Estimation Using Advanced Data and Models Analysis

For this advanced level of analysis, the expert can take advantage of the methodology's flexibility to (1) include a more refined inventory of the railway system pertaining to the area of study, and (2) include component-specific and system-specific fragility data. Default User-Supplied Data Analysis damage algorithms can be modified, or replaced, to incorporate improved information about key components of a railway system, such as urban stations. Similarly, better restoration curves can be developed, given knowledge of available resources and a more accurate layout of the railway network within the local topographic and geological conditions (i.e., if the redundancy and importance of railway components of the network are known).

7.2.10 References

Applied Technology Council, "Earthquake Damage Evaluation Data for California", ATC-13, Redwood City, CA, 1985.

G&E Engineering Systems, Inc. (G&E), "NIBS Earthquake Loss Estimation Methods, Technical Manual, Transportation Systems (Railway Systems)", May 1994.

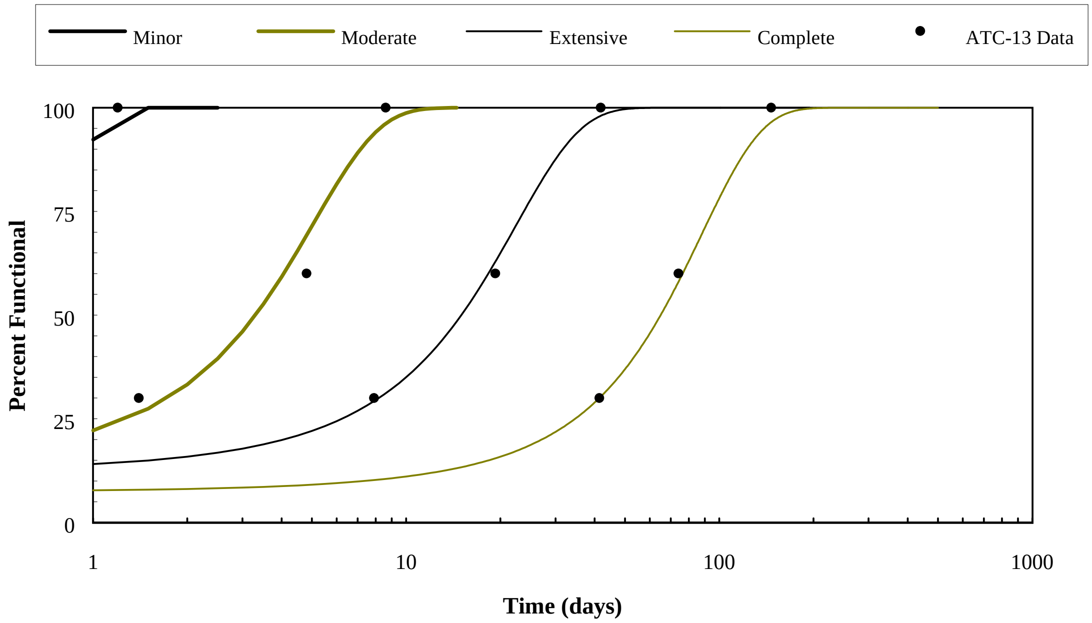


Figure 7.11 Restoration Curves for Railway Tracks/Roadbeds.

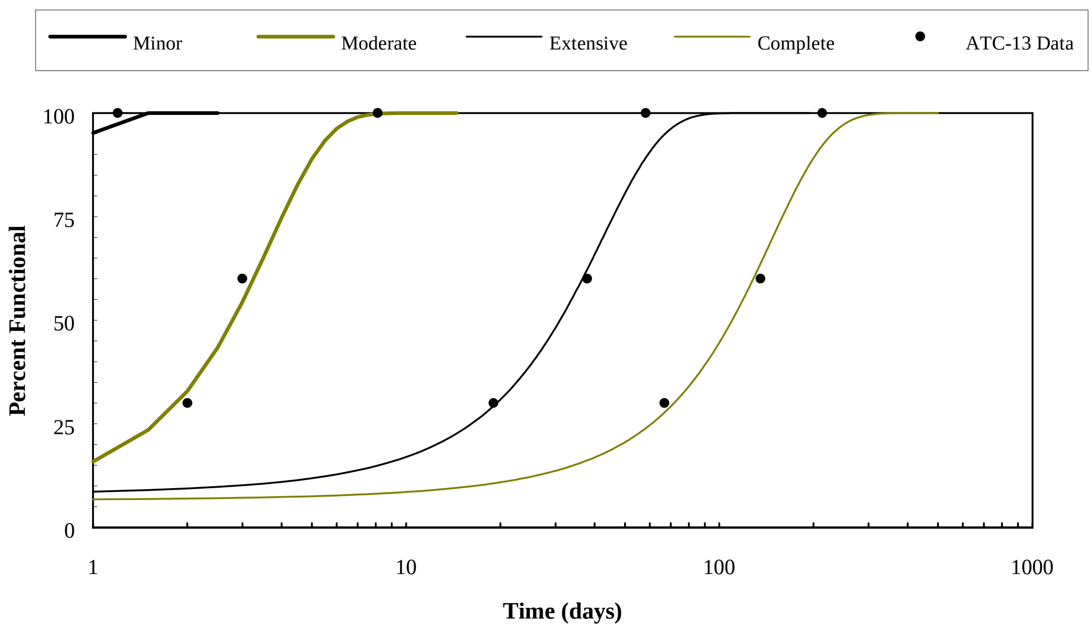


Figure 7.12 Restoration Curves for Railway Bridges.

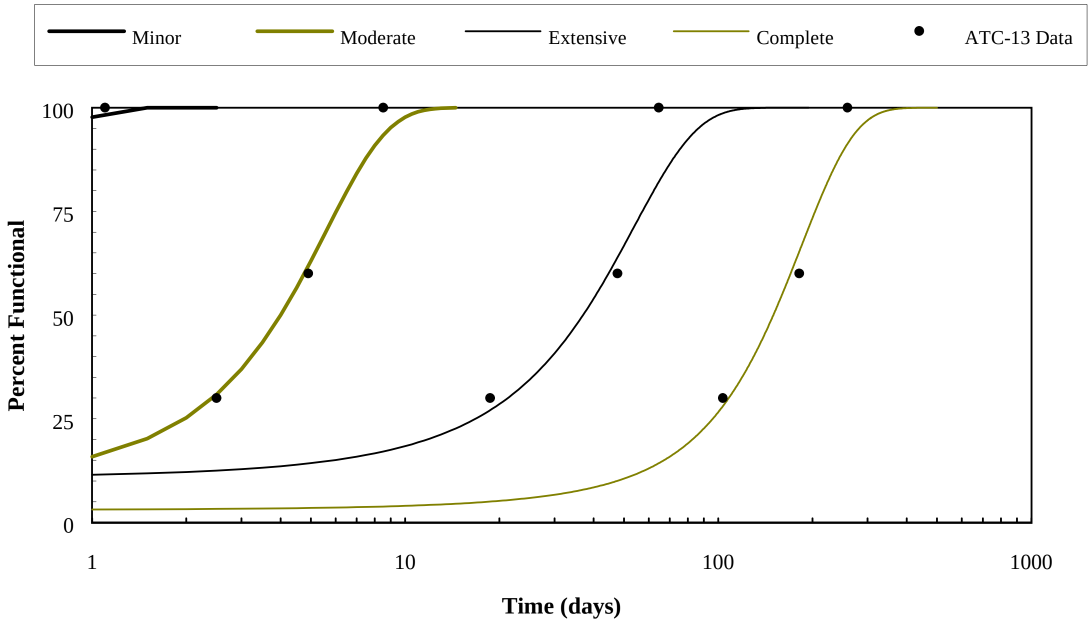


Figure 7.13 Restoration Curves for Railway Tunnels.

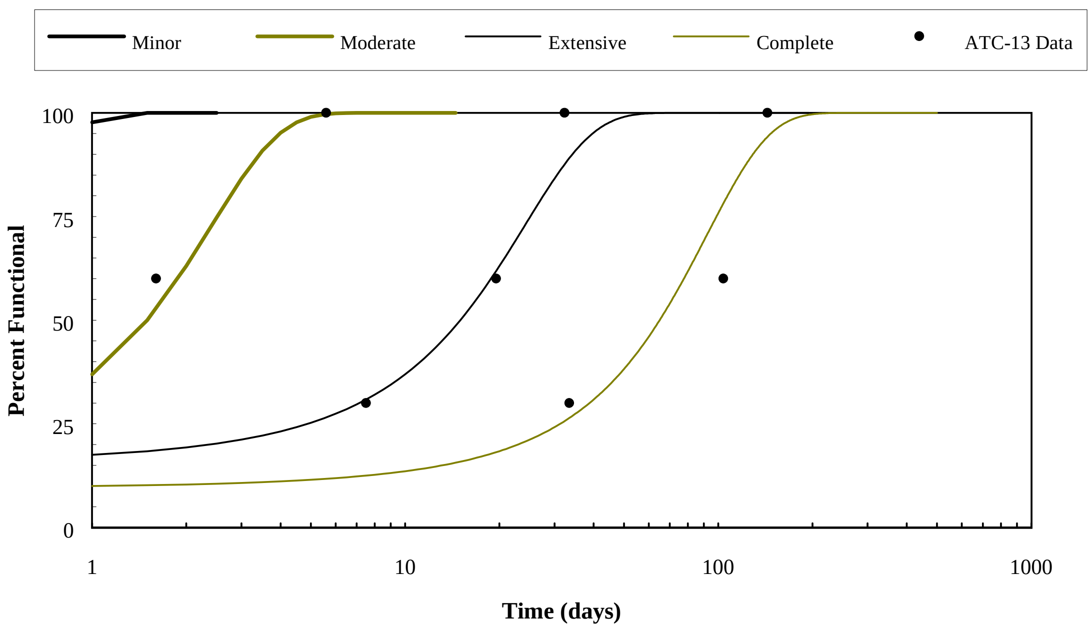


Figure 7.14 Restoration Curves for Railway Facilities.

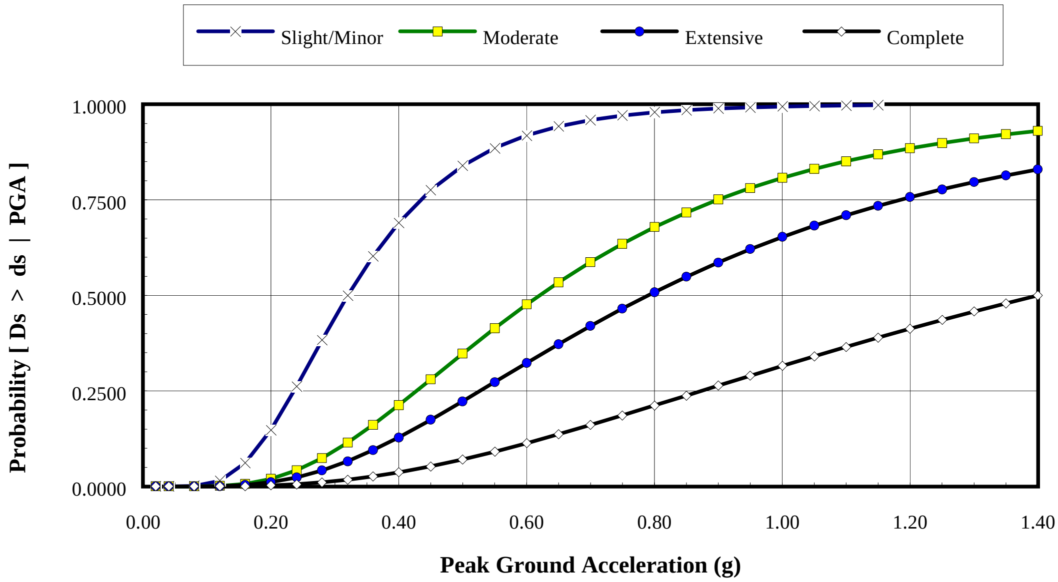


Figure 7.15 Fragility Curves at Various Damage States for Seismically Designed Railway Bridges Subject to Peak Ground Acceleration.

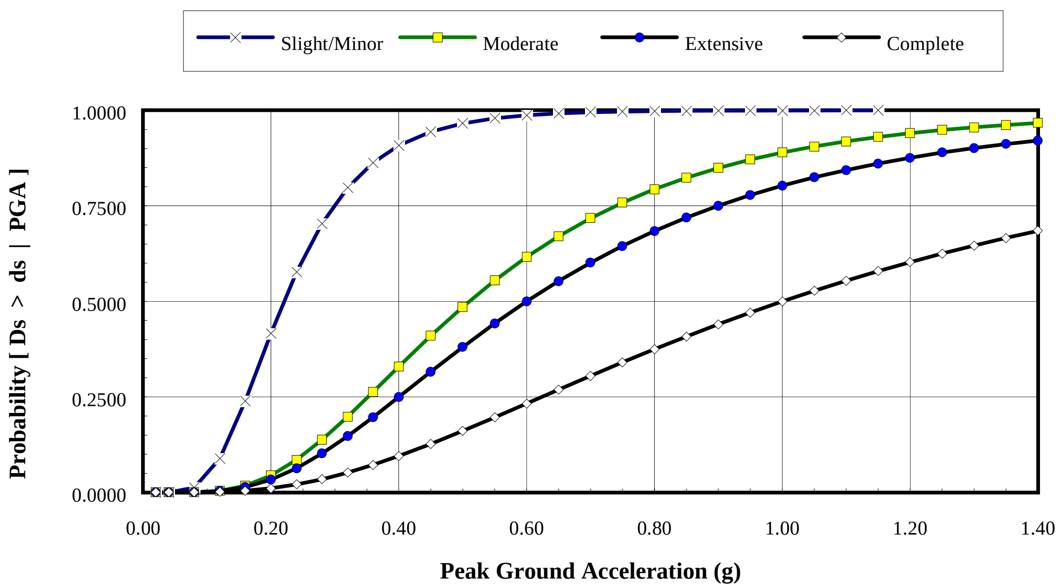


Figure 7.16 Fragility Curves at Various Damage States for Conventionally Designed Railway Bridges Subject to Peak Ground Acceleration.

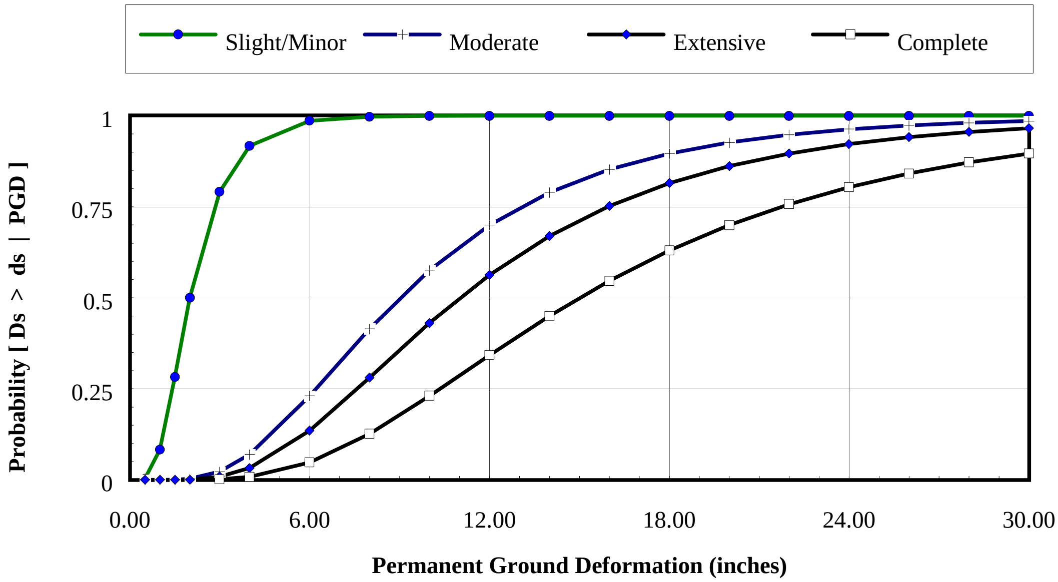


Figure 7.17 Fragility Curves at Various Damage States for Seismically-Designed Railway Bridges Subject to Permanent Ground Deformation.

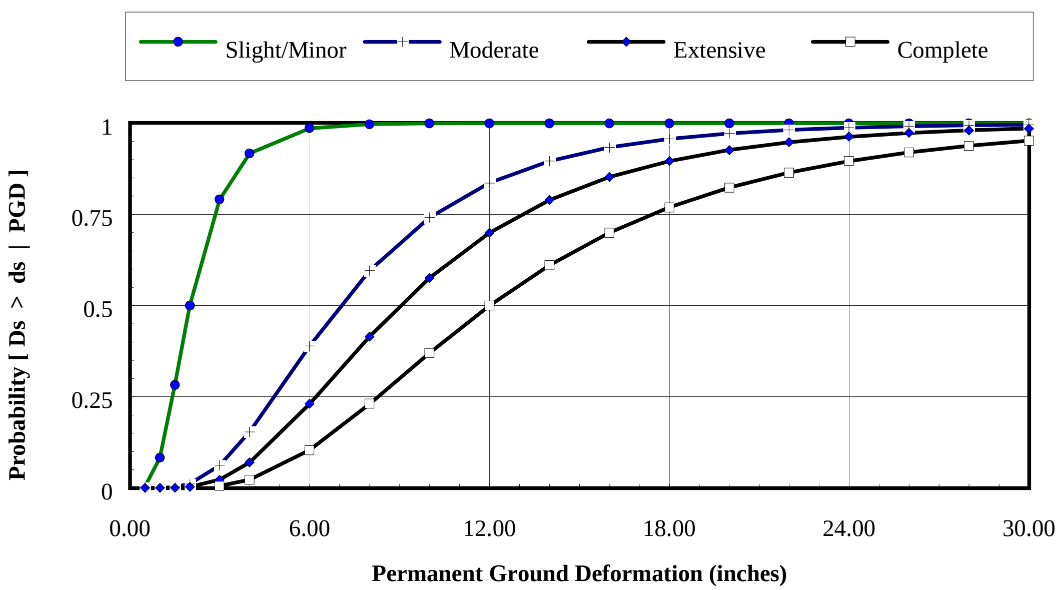


Figure 7.18 Fragility Curves at Various Damage States for Conventionally-Designed Railway Bridges Subject to PGD.

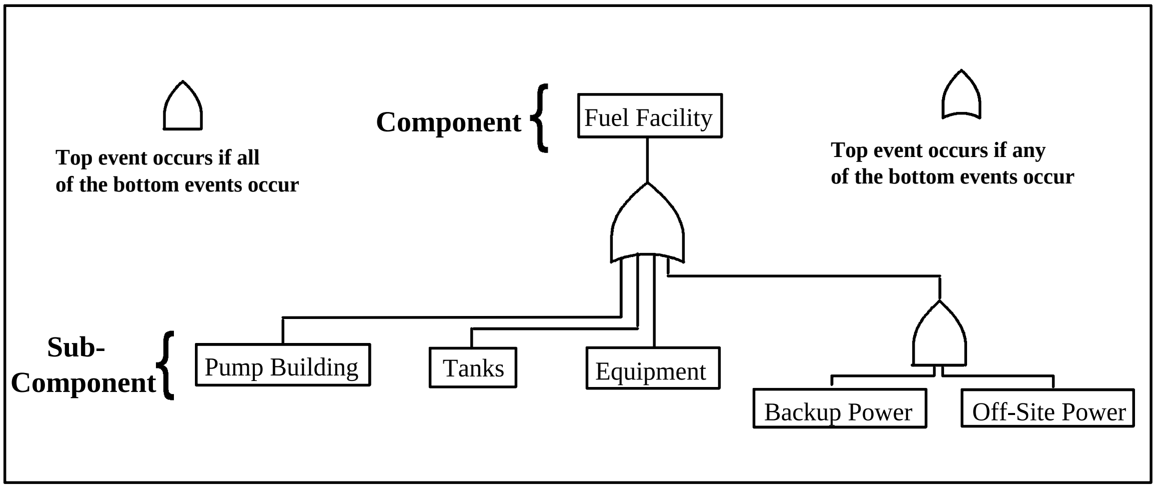


Figure 7.19a Fault Tree for Moderate Damage to Fuel Facilities with Anchored Equipment and Backup Power.

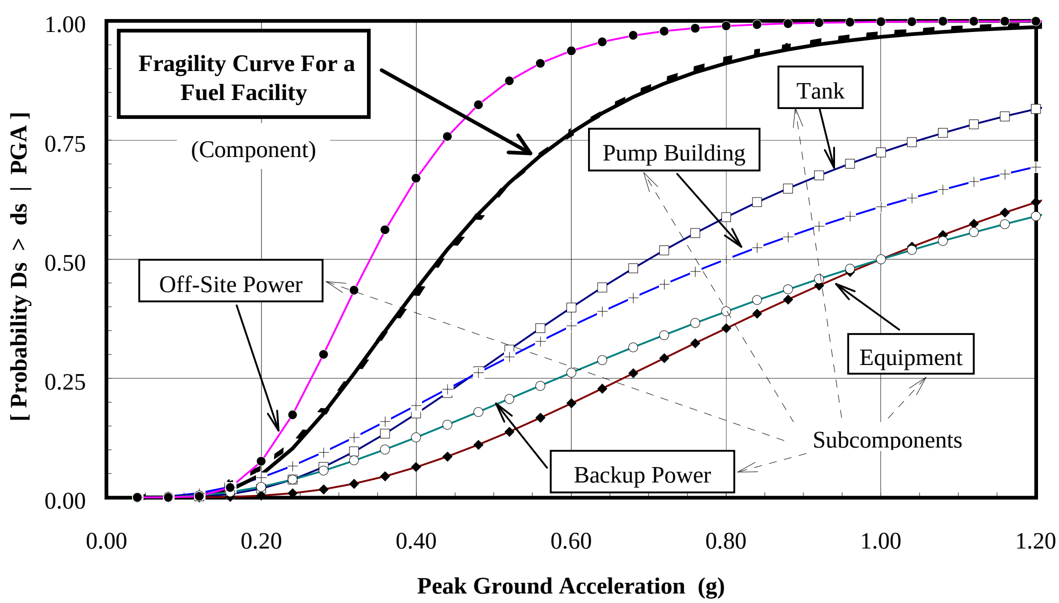


Figure 7.19b An Example of Fitting a Lognormal Curve (solid line) to a Fuel Facility Fragility Curve (dotted line).

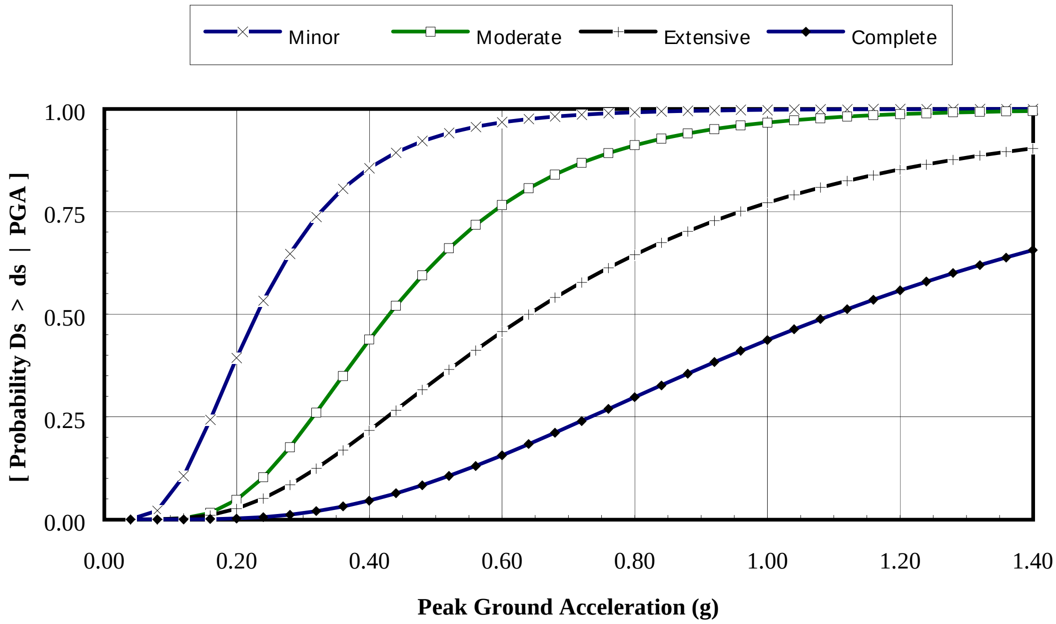


Figure 7.20.a Fragility Curves at Various Damage States for Fuel Facility with Anchored Components and Backup Power.

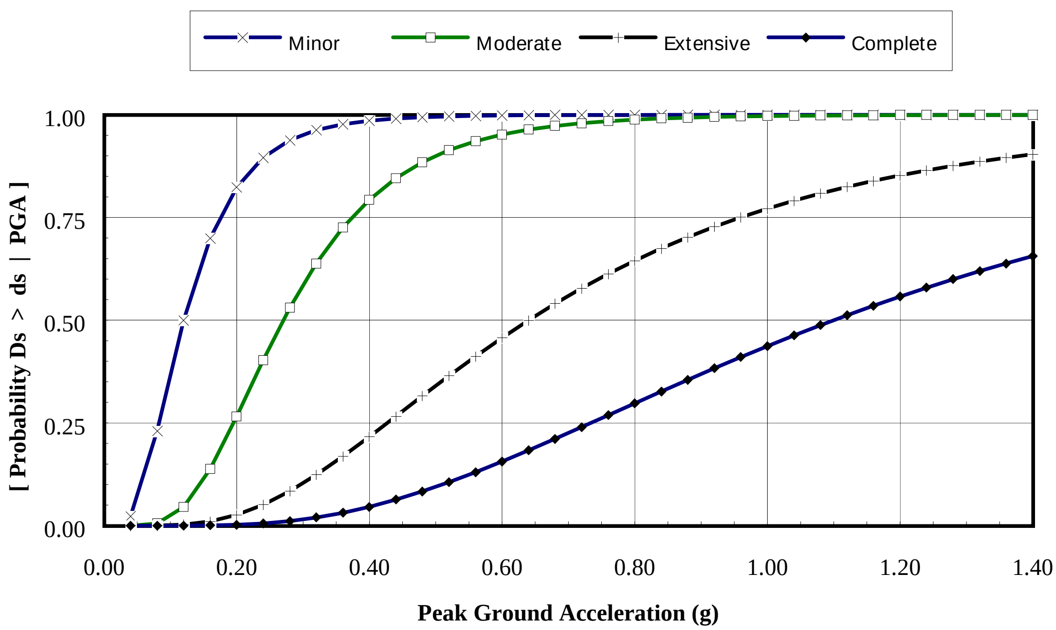


Figure 7.20.b Fragility Curves at Various Damage States for Fuel Facility with Anchored Components but no Backup Power.

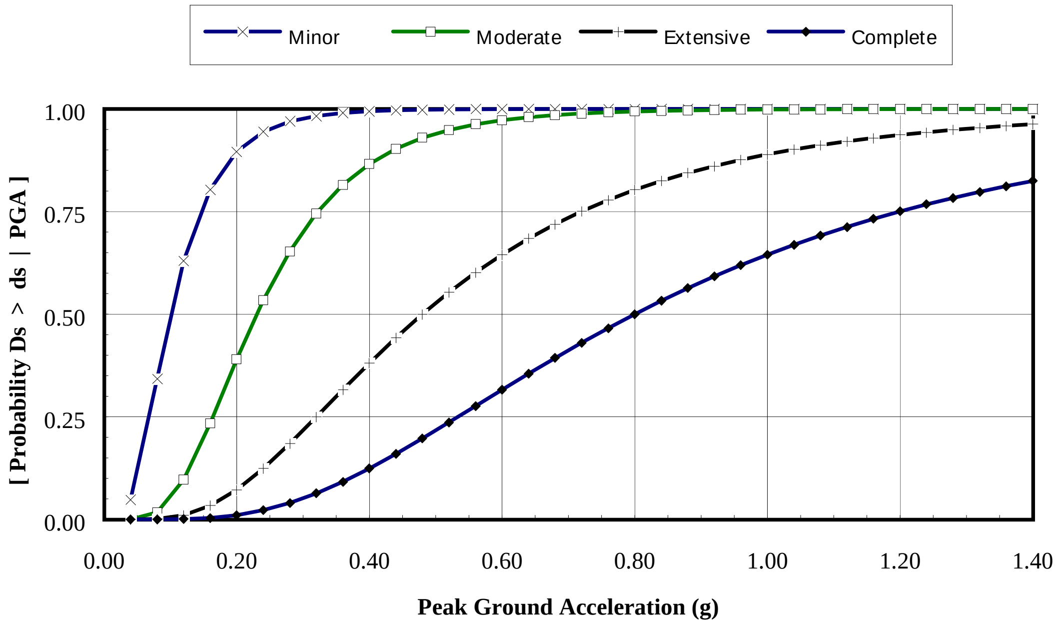


Figure 7.20.c Fragility Curves at Various Damage States for Fuel Facility with Unanchored Components and Backup Power.

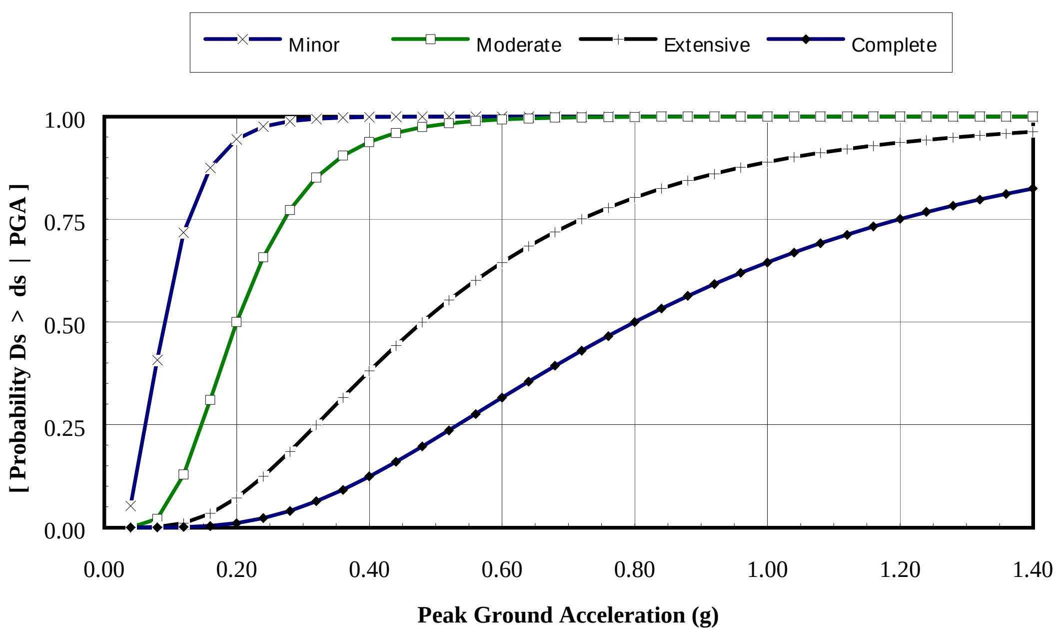


Figure 7.20.d Fragility Curves at Various Damage States for Fuel Facility with Unanchored Components and no Backup Power.

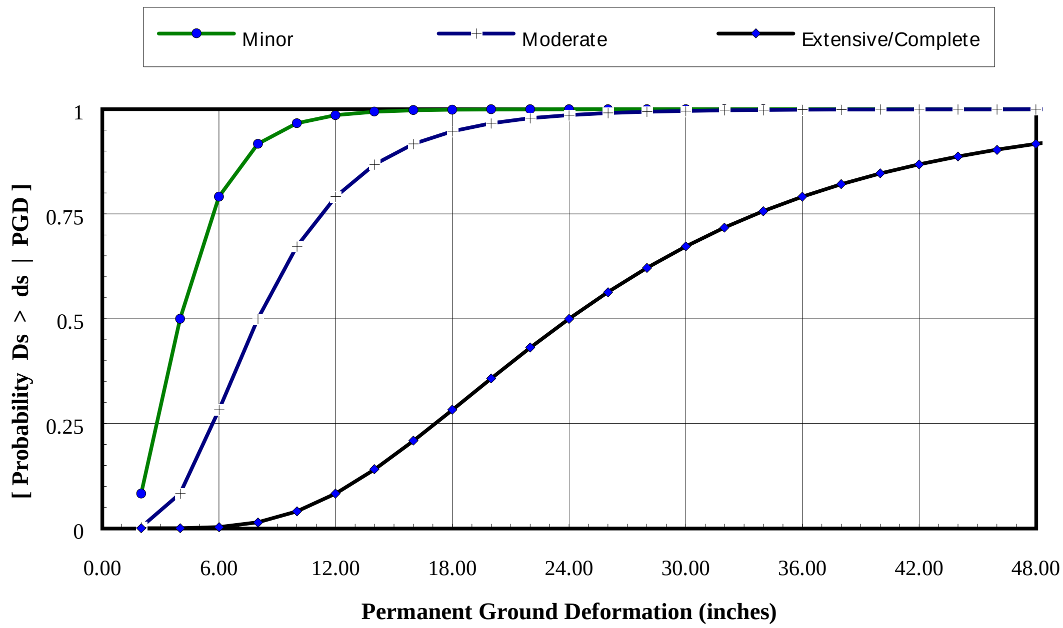


Figure 7.20.e Fragility Curves at Various Damage States for Fuel Facility with Buried Tanks Subject to Permanent Fround Deformation.

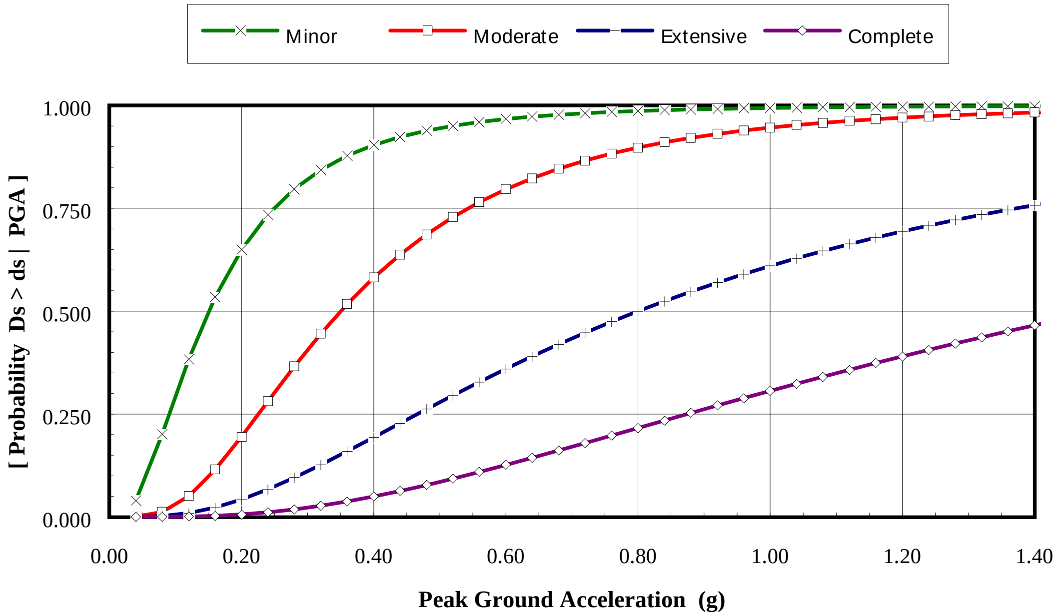


Figure 7.21.a Fragility Curves at Various Damage States for Dispatch Facility with Anchored Components and Backup Power.

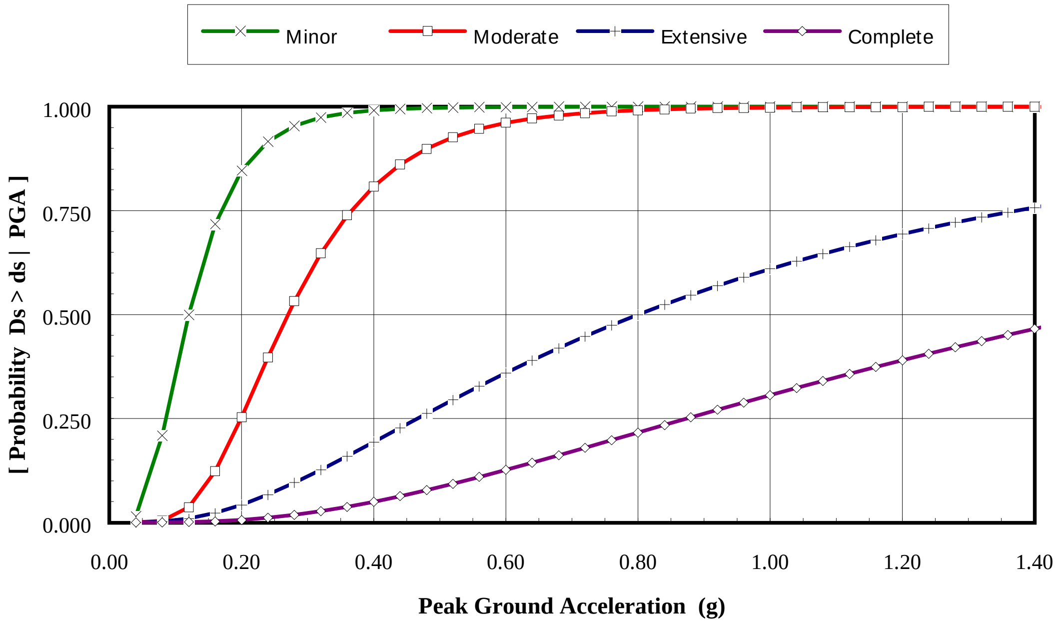


Figure 7.21.b Fragility Curves at Various Damage States for Dispatch Facility with Anchored Components but no Backup Power.

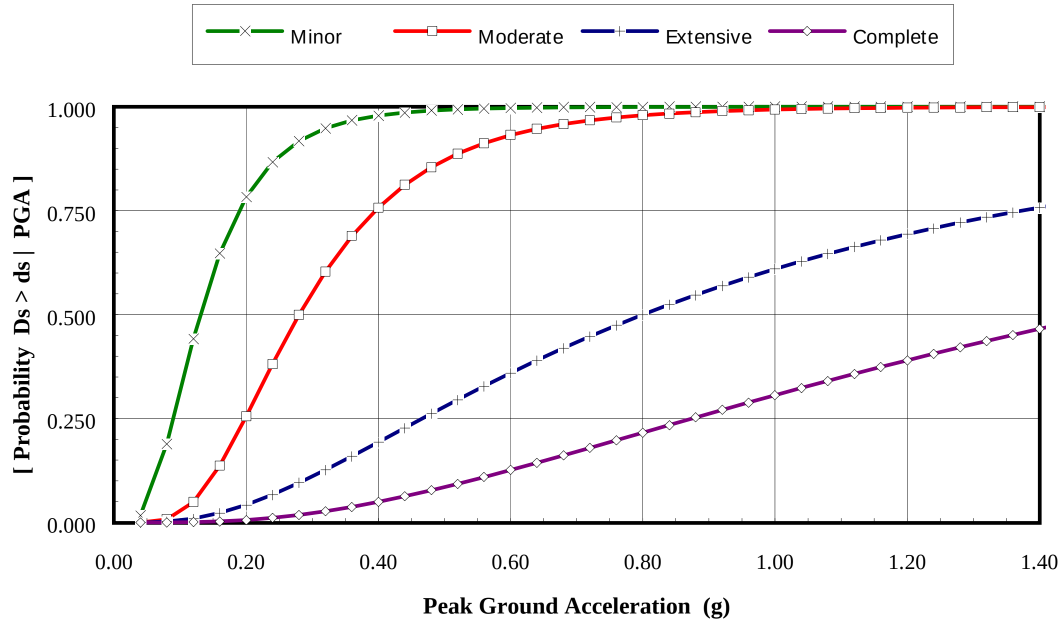


Figure 7.21.c Fragility Curves at Various Damage States for Dispatch Facility with Unanchored Components and Backup Power.

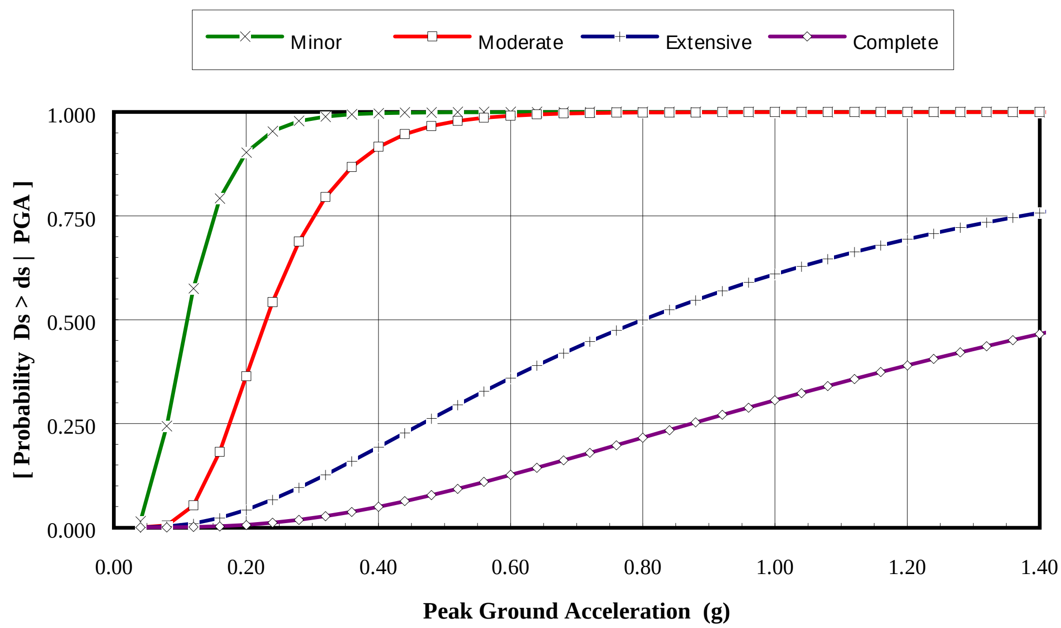


Figure 7.21.d Fragility Curves at Various Damage States for Dispatch Facility with Unanchored Components and no Backup Power.

7.3 Light Rail Transportation System

7.3.1 Introduction

This section presents an earthquake loss estimation methodology for a light rail transportation system. Like railway systems, light rail systems consist of railway tracks/roadbeds, bridges, tunnels, maintenance facilities, dispatch facilities and DC power substations. Therefore, the only difference in the case of light rail systems is in the fuel facilities, which are DC power substations.

7.3.2 Scope

The scope of this section includes development of methods for estimation of earthquake damage to a light rail transportation system given knowledge of the system's components, the classification of each component (e.g., for dispatch facilities, whether the facility's equipment is anchored or not), and the ground motion (i.e. peak ground acceleration and/or permanent ground deformation).

Damage states describing the level of damage to each light rail system component are defined (i.e. slight, moderate, extensive or complete). Damage states are related to damage ratio (defined as ratio of repair to replacement cost) for evaluation of direct economic loss. Component restoration curves are provided for each damage state to evaluate loss of function.

Fragility curves are developed for each type of light rail system component. These curves describe the probability of reaching or exceeding each damage state given the level of ground motion.

Interdependence of components on overall system functionality is not addressed by the methodology. Such considerations require a system (network) analysis that would be performed separately by a light rail system expert as an advanced study.

7.3.3 Input Requirements and Output Information

Required input to estimate damage to light rail systems includes the following items:

<u>Light Rail Tracks/Roadbeds</u>

- Geographical location of railway links [longitude and latitude of end nodes]
- Permanent ground deformation (PGD) at roadbed link

<u>Light Rail Bridges</u>

- Geographical location of bridge [longitude and latitude]
- Spectral values and PGD at bridge
- Bridge classification

Light Rail Tunnels

- Geographical location of tunnels [longitude and latitude]
- PGA and PGD at tunnel
- Tunnel Classification

Light Rail Facilities (DC substations, maintenance and dispatch facilities)

- Geographical location of facilities [longitude and latitude]
- PGA and PGD at facility
- Classification

Direct damage output for light rail systems includes probability estimates of (1) component functionality and (2) physical damage, expressed in terms of the component's damage ratio. Note that damage ratios, which are the inputs to direct economic loss methods, are described in section 15.3 of Chapter 15.

Component functionality is described by the probability of being in a damage state (immediately following the earthquake) and by the associated fraction or percentage of the component that is expected to be functional after a specified period of time.

7.3.4 Form of Damage Functions

Damage functions or fragility curves for all light rail system components mentioned above are modeled as lognormal functions that give the probability of reaching or exceeding different levels of damage for a given level of ground motion. Each fragility curve is characterized by a median value of ground motion (or failure) and an associated dispersion factor (lognormal standard deviation). Ground motion is quantified in terms of peak ground acceleration (PGA) and ground failure is quantified in terms of permanent ground displacement (PGD).

- Fragility curves for tracks/roadbeds are the same as for railway tracks/roadbeds.
- Fragility curves for bridges are the same as for railway bridges.
- Fragility curves for tunnels are the same as for railway tunnels.
- Fragility curves for maintenance and dispatch facilities are the same as for railway maintenance and dispatch facilities.
- Fragility curves for DC power substations are defined in terms of PGA and PGD.

7.3.5 Description of Light Railway System Components

A light rail system consists mainly of six components: tracks/roadbeds, bridges, tunnels, maintenance facilities, dispatch facilities, and DC power substations. The first five are the same as for railway systems and are already described in Section 7.2. Therefore, only DC substations will be described in this subsection.

<u>DC Power Substations</u>

Light rail systems use electric power and have low voltage DC power substations. DC power is used by the light rail system's electrical distribution system. The DC power substations consist of electrical equipment, which convert the local electric utility AC power to DC power. Two types of DC power stations are considered. These are: (1) DC power stations with anchored (seismically designed) components and (2) DC power stations with unanchored (which are not seismically designed) components.

7.3.6 Definitions of Damage States

A total of five damage states are defined for light rail system components. These are none (ds_1), slight/minor (ds_2), moderate (ds_3), extensive (ds_4) and complete (ds_5).

<u>Slight or Minor Damage</u> (ds_2)

- <u>For tracks/roadbeds</u>, ds_2 is defined similar to railway tracks.
- <u>For light rail bridges</u>, ds_2 is defined similar to railway bridges.
- <u>For light rail tunnels</u>, ds_2 is defined similar to highway tunnels.
- <u>For light rail system facilities</u>,

  ◊ For maintenance facilities, ds_2 is defined similar to railway maintenance facilities.

  ◊ For dispatch facilities, ds_2 is defined similar to railway dispatch facilities.

  ◊ For DC power substations with anchored or unanchored components, ds_2 is defined by loss of off-site power for a very short period, or slight damage to building.

<u>Moderate Damage</u> (ds_3)

- <u>For tracks/roadbeds</u>, ds_3 is defined similar to railway tracks.
- <u>For light rail bridges</u>, ds_3 is defined similar to railway bridges.
- <u>For light rail tunnels</u>, ds_3 is defined similar to highway tunnels.
- <u>For light rail system facilities</u>,

◊ For maintenance facilities, ds_3 is defined similar to railway maintenance facilities.

◊ For dispatch facilities, ds_3 is defined similar to railway dispatch facilities.

◊ For DC power substations with anchored or unanchored components, ds_3 is defined by loss of off-site power for few days, considerable damage to equipment, or moderate damage to building.

Extensive Damage (ds_4)

- For tracks/roadbeds, ds_4 is defined similar to railway tracks.
- For light rail bridges, ds_4 is defined similar to railway bridges.
- For light rail tunnels, ds_4 is defined similar to highway tunnels.
- For light rail system facilities,

◊ For maintenance facilities, ds_4 is defined similar to railway maintenance facilities.

◊ For dispatch facilities, ds_4 is defined similar to railway dispatch facilities.

◊ For DC power substations with anchored or unanchored components, ds_4 is defined by extensive building damage.

Complete Damage (ds_5)

- For tracks/roadbeds, ds_5 is defined similar to railway tracks.
- For light rail bridges, ds_5 is defined similar to railway bridges.
- For light rail tunnels, ds_5 is defined similar to highway tunnels.
- For light rail system facilities,

◊ For maintenance facilities, ds_5 is defined similar to railway maintenance facilities.

◊ For dispatch facilities, ds_5 is defined similar to railway dispatch facilities.

◊ For DC power substations with anchored or unanchored components, ds_5 is defined by complete building damage.

7.3.7 Component Restoration Curves

The restoration curves for light rail tracks/roadbeds, bridges, tunnels, and facilities are assumed to be the same as those for railway system components.

7.3.8 Development of Damage Functions

Fragility curves for light rail system components are defined with respect to classification and ground motion parameter. Again, except for DC power stations, damage functions of the other light rail system components have been already established in either section 7.1 (highway systems) or section 7.2 (railway systems).

Damage functions for Light Rail Tracks/Roadbeds

See damage functions for railway tracks/roadbeds.

Damage Functions for Light Rail Bridges

See damage functions for railway bridges.

Damage Functions for Light Rail Tunnels

See damage functions for highway tunnels.

Damage Functions for Light Rail System Facilities

Damage functions for light rail system facilities are defined in terms of PGA and PGD. Note that ground failure (PGD) related damage functions for these facilities are assumed to be similar to those described for railway system facilities in section 7.2.8.

PGA Related Damage Functions for Maintenance Facilities

Maintenance facilities for light rail systems are mostly made of steel braced frames. Since no default inventory is provided for these facilities, the user will be expected to provide the appropriate mapping between these facilities whose damage functions are listed in Table 7.7 of section 7.2.8 and their model building types.

PGA Related Damage Functions for Dispatch Facilities

See damage functions for railway dispatch facilities.

PGA Related Damage Functions for DC Power Substations

Fragility curves for the two types of DC power substations are developed based on the type of damage incurred by the DC power substation subcomponents (building, equipment, and off-site power for interaction effects). These two types are DC power substations with unanchored equipment, and DC power substations with unanchored equipment. Medians and dispersions of damage functions to DC power substations subcomponents are summarized in Tables C.7.1 and C.7.2 of Appendix 7C. Component fragility curves are obtained using the same methodology as used before. That is, each fragility curve is determined by a lognormal curve that best fits the results of the Boolean combination. It should be mentioned that the Boolean logic is implicitly presented within the definition of a particular damage state. The medians and dispersions of the damage functions for anchored and unanchored DC power substations are shown in Table 7.13 and plotted in Figures 7.22.a and 7.22.b.

Table 7.13 Damage Algorithms for DC Power Substations

Peak Ground Acceleration			
Classification	**Damage State**	**Median (g)**	**β**
Substation with Anchored Components	slight	0.12	0.55
	moderate	0.27	0.45
	extensive	0.80	0.80
	complete	1.50	0.80
Substation with Unnchored Components	slight	0.11	0.50
	moderate	0.23	0.40
	extensive	0.80	0.80
	complete	1.50	0.80

7.3.9 Guidance for Loss Estimation Using Advanced Data and Models Analysis

For this type of analysis, the expert can use the methodology developed with the flexibility to (1) include a refined inventory of the light rail system pertaining to the area of study, and (2) include component specific and system specific fragility data. Default User-Supplied Data Analysis damage algorithms can be modified or replaced to accommodate any specified key component of a light railway system, such as a bridge. Similarly, better restoration curves could be developed given knowledge of available resources and a more accurate layout of the light rail network within the local topographic and geological conditions (i.e. redundancy and importance of a light railway component in the network are known).

7.3.10 References

Applied Technology Council, "Earthquake Damage Evaluation Data for California", ATC-13, Redwood City, CA, 1985.

G & E Engineering Systems, Inc. (G & E), "NIBS Earthquake Loss Estimation Methods, Technical Manual, Transportation Systems", May 1994.

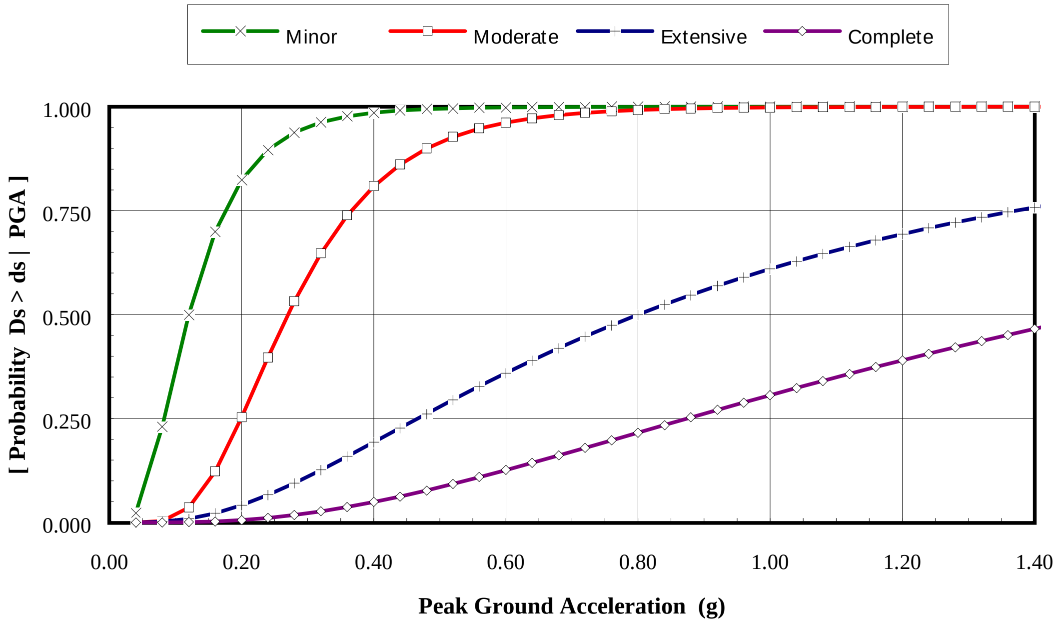


Figure 7.22.a Fragility Curves at Various Damage States for DC Power Substations with Anchored Components.

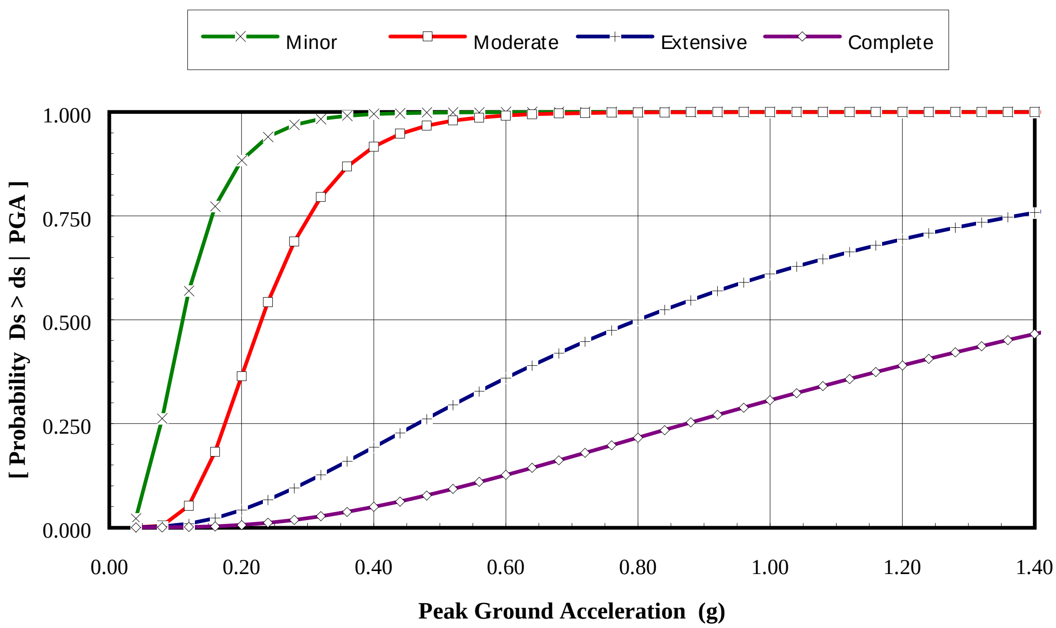


Figure 7.22.b Fragility Curves at Various Damage States for DC Power Substations with Unanchored Components.

7.4 Bus Transportation System

7.4.1 Introduction

This section presents a loss estimation methodology for a bus transportation system during earthquakes. Bus facilities consist of maintenance, fuel, and dispatch facilities. The facilities may sustain damage due to ground shaking or ground failure. Major losses can occur if bus maintenance buildings collapse, and operational problems may arise if a dispatch facility is damaged.

7.4.2 Scope

The scope of this section includes development of methods for estimation of earthquake damage to a bus transportation system given knowledge of components (i.e., fuel, maintenance, and dispatch facilities with or without backup power), classification (i.e. for fuel facilities, anchored or unanchored components), and the ground motion (i.e. peak ground acceleration and/or permanent ground deformation).

Damage states describing the level of damage to each of the bus system components are defined (i.e. slight, moderate, extensive or complete). Damage states are related to damage ratio (defined as ratio of repair to replacement cost) for evaluation of direct economic loss. Component restoration curves are provided for each damage state to evaluate loss of function. Restoration curves describe the fraction or percentage of the component that is expected to be open or operational as a function of time following the earthquake. For bus systems, the restoration is dependent upon the extent of damage to the fuel, maintenance, and dispatch facilities.

Fragility curves are developed for each class of bus system component. These curves describe the probability of reaching or exceeding each damage state given the level of ground motion. Based on these fragility curves, a method for assessing functionality of each of the three bus system components is presented.

Interdependence of components on overall system functionality is not addressed by the methodology. Such considerations require a system (network) analysis that would be performed separately by a bus system expert as an advanced study.

7.4.3 Input Requirements and Output Information

Required input to estimate damage to bus systems includes the following items:

Urban Stations

- Geographical location of site
- Spectral values and PGD at station
- Classification

Fuel Facilities

- Geographical location of site
- PGA and PGD at facility
- Classification (i.e. with or without anchored equipment and backup power)

Maintenance Facilities

- Geographical location of site
- Spectral values and PGD at facility
- Classification (i.e. building type)

Dispatch Facilities

- Geographical location of each warehouse
- PGA and PGD at facility
- Classification (i.e. with or without anchored equipment and backup power)

Direct damage output for bus systems includes probability estimates of (1) component functionality and (2) physical damage, expressed in terms of the component's damage ratio.

Component functionality is described by the probability of being in a damage state (immediately following the earthquake) and by the associated fraction or percentage of the component that is expected to be functional after a specified period of time.

7.4.4 Form of Damage Functions

Damage functions or fragility curves for all three bus system components, mentioned above, are lognormal functions that give the probability of reaching or exceeding different levels of damage for a given level of ground motion. Each fragility curve is characterized by a median value of ground motion (or failure) and an associated dispersion factor (lognormal standard deviation). Ground motion is quantified in terms of peak ground acceleration (PGA) and ground failure is quantified in terms of permanent ground displacement (PGD).

- For urban stations, the fragility curves are defined in terms of Spectral values and PGD.

- For fuel facilities, the fragility curves are defined in terms of PGA and PGD.

- For maintenance facilities, the fragility curves are defined in terms of Spectral values and PGD.

- For dispatch facilities, the fragility curves are defined in terms of PGA and PGD.

Definitions of various damage states and the methodology used in deriving all these fragility curves are presented in the following section.

7.4.5 Description of Bus System Components

A bus system consists mainly of four components: urban stations, fuel facilities, maintenance facilities, and dispatch facilities. This section provides a brief description of each.

<u>Urban Stations</u>

These are mainly buildings structures.

<u>Bus System Fuel Facilities</u>

Fuel facility consists of fuel storage tanks, buildings, pump equipment and buried pipe, and, sometimes, backup power. The fuel facility functionality is determined with a fault tree analysis considering redundancies and sub-component behavior. The same classes assumed for railway fuel facilities are assumed here. These are listed in Table 3.9.

<u>Bus System Maintenance Facilities</u>

Maintenance facilities for bus systems are mostly made of steel braced frames. The same classes assumed for railway maintenance facilities are assumed here.

<u>Bus System Dispatch Facilities</u>

The same classes assumed for railway dispatch facilities are assumed here. These are listed in Table 3.9.

7.4.6 Definitions of Damage States

A total of five damage states are defined for highway system components. These are none (ds_1), slight/minor (ds_2), moderate (ds_3), extensive (ds_4) and complete (ds_5).

<u>Slight Damage</u> (ds_2)

◊ For urban stations, ds_2 is defined similar to railway urban stations.

◊ For fuel facilities, ds_2 is defined similar to railway fuel facilities.

◊ For maintenance facilities, ds_2 is defined similar to railway maintenance facilities.

◊ For dispatch facilities, ds_2 is defined similar to railway dispatch facilities.

<u>Moderate Damage</u> (ds_3)

◊ For urban stations, ds_3 is defined similar to railway urban stations.

◊ For fuel facilities, ds_3 is defined similar to railway fuel facilities.

◊ For maintenance facilities, ds_3 is defined similar to railway maintenance facilities.

◊ For dispatch facilities, ds_3 is defined similar to railway dispatch facilities.

<u>Extensive Damage</u> (ds_4)

◊ For urban stations, ds_4 is defined similar to railway urban stations.

◊ For fuel facilities, ds_4 is defined similar to railway fuel facilities.

◊ For maintenance facilities, ds_4 is defined similar to railway maintenance facilities.

◊ For dispatch facilities, ds_4 is defined similar to railway dispatch facilities.

<u>Complete Damage</u> (ds_5)

◊ For urban stations, ds_5 is defined similar to railway urban stations.

◊ For fuel facilities, ds_5 is defined similar to railway fuel facilities.

◊ For maintenance facilities, ds_5 is defined similar to railway maintenance facilities.

◊ For dispatch facilities, ds_5 is defined similar to railway dispatch facilities.

7.4.7 Component Restoration Curves

Restoration Curves are developed based on a best fit to ATC-13 damage data for the social functions SF 26a through SF 26d, consistent with damage states defined in the previous section. Normal distribution functions are developed using the ATC-13 data for the mean time for 30%, 60% and 100% restoration of different sub-components in different damage states. The restoration curves for bus transportation systems are similar to those of railway transportation systems. Means and dispersions of these restoration functions are given in Tables 7.10.a. Discretized restoration functions are shown in Table 7.10.b, where the percentage restoration is shown at discrete times.

7.4.8 Development of Damage Functions

Fragility curves for bus system components are defined with respect to classification and ground motion parameter.

Damage Functions for Bus System Urban Stations

Urban stations are classified based on the building structural type. Damage functions for bus system urban stations are similar to those for the railway transportation system (see Section 7.2.8).

Damage Functions for Bus System Fuel Facilities

Fuel facilities are classified based on two criteria: (1) whether the sub-components comprising the fuel facilities are anchored or unanchored and (2) whether backup power exists in the facility. Damage functions for bus system fuel facilities are similar to those for the railway transportation system (see Section 7.2.8).

Damage Functions for Bus System Maintenance Facilities

The PGA and PGD median values for the damage states of maintenance facilities are similar to those of light rail maintenance facilities presented in Section 7.3.8.

Damage Functions for Bus System Dispatch Facility

The PGA and PGD median values for the damage states of dispatch facilities are similar to those of railway dispatch facilities given in Section 7.2.8.

7.4.9 Guidance for Loss Estimation using Advanced Data and Models Analysis

For this level of analysis, the expert can use the methodology developed with the flexibility to: (1) include a refined inventory of the bus system pertaining to the area of study, and (2) include component specific and system specific fragility data. Default User-Supplied Data Analysis damage algorithms can be modified or replaced to accommodate any specified key component of a bus system, such as a warehouse. Similarly, better restoration curves could be developed given knowledge of available resources and a more accurate layout of the bus transportation network within the local topographic and geological conditions (i.e., redundancy and importance of a bus system component in the network are known).

7.4.10 References

Applied Technology Council, "Earthquake Damage Evaluation Data for California", ATC-13, Redwood City, CA, 1985.

G & E Engineering Systems, Inc. (G & E), "NIBS Earthquake Loss Estimation Methods, Technical Manual, Transportation Systems", May 1994.

7.5 Port Transportation System

7.5.1 Introduction

This section presents a loss estimation methodology for a port transportation system. Port facilities consist of waterfront structures (e.g., wharfs, piers and seawalls); cranes and cargo handling equipment; fuel facilities; and warehouses. In many cases, these facilities were constructed prior to widespread use of engineered fills; consequently, the wharf, pier, and seawall structures are prone to damage due to soil failures such as liquefaction. Other components may be damaged due to ground shaking as well as ground failure.

7.5.2 Scope

The scope of this section includes developing methods for estimating earthquake damage to a port transportation system given knowledge of components (i.e., waterfront structures, cranes and cargo handling equipment, fuel facilities, and warehouses), classification (i.e. for fuel facilities, anchored or unanchored components, with or without back-up power), and the ground motion (i.e. peak ground acceleration and/or permanent ground deformation).

Damage states describing the level of damage to each of the port system components are defined (i.e. slight, moderate, extensive or complete). Damage states are related to damage ratio (defined as ratio of repair to replacement cost) for evaluation of direct economic loss. Component restoration curves are provided for each damage state to evaluate loss of function. Restoration curves describe the fraction or percentage of the component that is expected to be open or operational as a function of time following the earthquake. For ports the restoration is dependent upon the extent of damage to the waterfront structures, cranes/cargo handling equipment, fuel facilities, and warehouses. From the standpoint of functionality of the port, the user should consider the restoration of only the waterfront structures and cranes since the fuel facilities and warehouses are not as critical to the functionality of the port.

Fragility curves are developed for each class of port system component. These curves describe the probability of reaching or exceeding a certain damage state given the level of ground motion. Based on these fragility curves, a method for assessing functionality of each of the four port system components is presented.

Interdependence of components on overall system functionality is not addressed by the methodology. Such considerations require a system (network) analysis that would be performed separately by a port system expert as an advanced study.

7.5.3 Input Requirements and Output Information

Required input to estimate damage to port systems includes the following items:

Waterfront Structures

- Geographic location of port (longitude and latitude)
- PGA & PGD
- Classification

Cranes/Cargo Handling Equipment

- Geographic location of port (longitude and latitude)
- PGA and PGD
- Classification (i.e. stationary or rail mounted)

Fuel Facilities

- Geographical location of facility [longitude and latitude]
- PGA and PGD
- Classification

Warehouses

- Geographical location of warehouse [longitude and latitude]
- PGA and PGD
- Classification (i.e. building type)

Direct damage output for port systems includes probability estimates of (1) component functionality and (2) physical damage, expressed in terms of the component's damage ratio. Damage ratios are used as inputs to direct economic loss methods, as described in section 15.3 of Chapter 15.

7.5.4 Form of Damage Functions

Damage functions or fragility curves for all four port system components, mentioned above, are lognormally distributed functions that give the probability of reaching or exceeding different levels of damage for a given level of ground motion. Each fragility curve is characterized by a median value of ground motion (or failure) and an associated dispersion factor (lognormal standard deviation). Ground motion is quantified in terms of peak ground acceleration (PGA) and ground failure is quantified in terms of permanent ground displacement (PGD).

- For waterfront structures, the fragility curves are defined in terms of PGD and PGA.

- For cranes/cargo handling equipment, the fragility curves are defined in terms of PGA and PGD.

- For fuel facilities, the fragility curves are defined in terms of PGA and PGD.

- For warehouses, the fragility curves are defined in terms of PGA and PGD.

Definitions of various damage states and the methodology used in deriving all these fragility curves are presented in the following section.

7.5.5 Description of Port Components

A port system consists of four components: waterfront structures, cranes/cargo handling equipment, fuel facilities, and warehouses. This section provides a brief description of each.

Waterfront Structures

This component includes wharves (port embankments), seawalls (protective walls from erosion), and piers (break-water structures which form harbors) that exist in the port system. Waterfront structures typically are supported by wood, steel or concrete piles. Many also have batter piles to resist lateral loads from wave action and impact of vessels. Seawalls are caisson walls retaining earth fill material.

Cranes and Cargo Handling Equipment

These are large equipment items used to load and unload freight from vessels. These are can be stationary or mounted on rails.

Port Fuel Facilities

The fuel facility consists mainly of fuel storage tanks, buildings, pump equipment, piping, and, sometimes, backup power. These are the same as those for railway systems presented in Section 7.2. The functionality of fuel systems is determined with a fault tree analysis, which considers redundancies and sub-component behavior, as it can be seen in Figures 7.18 and 7.19 of Section 7.2. Note that five types of fuel facilities in total are defined.

Warehouses

Warehouses are large buildings usually constructed of structural steel. In some cases, warehouses may be several hundred feet from the shoreline, while in other instances; they may be located on the wharf itself.

7.5.6 Definition of Damage States

A total of five damage states are defined for port system components. These are none (ds_1), slight/minor (ds_2), moderate (ds_3), extensive (ds_4) and complete (ds_5).

Slight/Minor Damage (ds_2)

- For waterfront structures, ds_2 is defined by minor ground settlement resulting in few piles (for piers/seawalls) getting broken and damaged. Cracks are formed on the surface of the wharf. Repair may be needed.
- For cranes/cargo handling equipment, ds_2 is defined by slight damage to structural members with no loss of function for the stationary equipment, while for the unanchored or rail mounted equipment, ds_1 is defined as minor derailment or misalignment without any major structural damage to the rail mount. Minor repair and adjustments may be required before the crane becomes operable.
- For fuel facilities, ds_2 is defined the same as for railway facilities.
- For warehouses, ds_2 is defined by slight damage to the warehouse building.

Moderate Damage (ds_3)

- For waterfront structures, ds_3 is defined as considerable ground settlement with several piles (for piers/seawalls) getting broken and damaged.
- For cranes/cargo handling equipment, ds_3 is defined as derailment due to differential displacement of parallel track. Rail repair and some repair to structural members is required.
- For fuel facilities, ds_3 is defined the same as for railway facilities.
- For warehouses, ds_3 is defined by moderate damage to the warehouse building.

Extensive Damage (ds_4)

- For waterfront structures, ds_4 is defined by failure of many piles, extensive sliding of piers, and significant ground settlement causing extensive cracking of pavements.
- For cranes/cargo handling equipment, ds_4 is defined by considerabe damage to equipment. Toppled or totally derailed cranes are likely to occcur. Replacement of structural members is required.
- For fuel facilities, ds_4 is defined same as for railway facilities.
- For warehouses, ds_4 is defined by extensive damage to warehouse building.

Complete Damage (ds_5)

- For waterfront structures, ds_5 is defined as failure of most piles due to significant ground settlement. Extensive damage is widespread at the port facility.

- For cranes/cargo handling equipment, ds_5 is the same as ds_4.
- For fuel facilities with buried tanks, ds_5 is the same as for railway facilities.
- For warehouses, ds_5 is defined by total damage to the warehouse building.

7.5.7 Component Restoration Curves

Restoration Curves are developed based on a best fit to ATC-13 damage data for social functions SF 28.a and SF 29.b, consistent with damage states defined in the previous section. Normal distribution functions are developed using the ATC-13 data for the mean time for 30%, 60% and 100% restoration of different sub-components in different damage states. Means and dispersions of these restoration functions are given in Table 7.14.a. The discretized restoration functions are given in Table 7.14.b, where the percentage restoration is shown at some specified time intervals. These restoration functions are shown in Figures 7.23 and 7.24. Figure 7.23 represents restoration curves for waterfront structures, while Figure 7.24 shows restorations curve for cranes and cargo handling equipment.

Table 7.14.a Restoration Functions for Port Sub-Components

Restoration Functions (All Normal Distributions)			
Classification	**Damage State**	**Mean (Days)**	**σ**
Buildings, Waterfront Structures	slight/minor	0.6	0.2
	moderate	3.5	3.5
	extensive	22	22
	complete	85	73
Cranes/Cargo Handling Equipment	slight/minor	0.4	0.35
	moderate	6	6
	extensive	30	30
	complete	75	55

Table 7.14.b Discretized Restoration Functions for Port Sub-Components

Discretized Restoration Functions						
Classification	**Damage State**	**1 day**	**3 days**	**7 days**	**30 days**	**90 days**
Buildings, Waterfront Structures	slight/minor	96	100	100	100	100
	moderate	24	43	84	100	100
	extensive	17	19	25	63	100
	complete	12	13	14	22	53
Cranes/Cargo Handling Equipment	slight/minor	96	100	100	100	100
	moderate	20	31	57	100	100
	extensive	17	18	22	50	100
	complete	9	10	11	21	62

7.5.8 Development of Damage Functions

Damage functions for port system facilities are defined in terms of PGA and PGD. Note that, unless it is specified otherwise, ground failure (PGD) related damage functions for these facilities are assumed to be similar to those described for railroad system facilities in section 7.2.8.

An example of how to combine PGD and PGA algorithms is presented in section 7.2.8.

Damage functions for Waterfront Structures

Damage functions for waterfront structures were established based on damagability of subcomponents, namely, piers, seawalls, and wharf. Fault tree logic and the lognormal best fitting technique were used in developing these fragility curves. The fault tree is implicitly described in the description of the damage state. The obtained damage functions are shown in Figure 7.25. Their medians and dispersions are presented in Table 7.15a. Subcomponent damage functions are given in Table 7.D.1 of Appendix 7D.

Table 7.15.a Damage Algorithms for Waterfront Structures

Permanent Ground Deformation			
Components	**Damage State**	**Median (in)**	**β**
Waterfront Structures (PWS1)	slight/minor	5	0.50
	moderate	12	0.50
	extensive	17	0.50
	complete	43	0.50

Damage Functions for Cranes and Cargo Handling Equipment

For cranes, a distinction is made between stationary and rail-mounted cranes. The medians and dispersions of damage functions are presented in Tables 7.15.b, while the fragility curves are shown in Figures 7.26 through 7.29.

Table 7.15.b Damage Algorithms for Cranes/Cargo Handling Equipment

Peak Ground Acceleration			
Classification	**Damage State**	**Median (g)**	**β**
Anchored/ Stationary (PEQ1)	slight/minor	0.3	0.6
	moderate	0.5	0.6
	extensive/complete	1.0	0.7
Unanchored/Rail mounted (PEQ2)	slight/minor	0.15	0.6
	moderate	0.35	0.6
	extensive/complete	0.8	0.7

Permanent Ground Deformation			
Classification	**Damage State**	**Median (in)**	**β**
Anchored/ Stationary (PEQ1)	slight/minor	3	0.6
	moderate	6	0.7
	extensive/complete	12.0	0.7
Unanchored/Rail mounted (PEQ2)	slight/minor	2	0.6
	moderate	4.0	0.6
	extensive/complete	10	0.7

Damage Functions for Port System Fuel Facilities

Damage funcitons for fuel facilities are similar to those developed for railway fuel facilities in Section 7.2.8.

PGA Related Damage Functions for Warehouses

Since no default inventory is provided for these facilities, the user will be expected to provide the appropriate mapping bewteen these facilities and the building types which are assumed to be the same as for railway maintenance facilities whose damage functions are listed in Table 7.7 of section 7.2.8.

7.5.9 Guidance for Loss Estimation using Advanced Data and Models Analysis

For this type of analysis, the expert can use the methodology developed with the flexibility to: (1) include a refined inventory of the port transportation system pertaining to the area of study, and (2) include component specific and system specific fragility data. Default User-Supplied Data Analysis damage algorithms can be modified or replaced to accommodate any specified key component of a port system, such as a warehouse. Similarly, better restoration curves could be developed given knowledge of available resources and a more accurate layout of the port network within the local topographic and geological conditions (i.e., redundancy and importance of a port system component in the network are known).

7.5.10 References

Applied Technology Council, "Earthquake Damage Evaluation Data for California", ATC-13, Redwood City, CA, 1985.

G & E Engineering Systems, Inc. (G & E), "NIBS Earthquake Loss Estimation Methods, Technical Manual, Transportation Systems", May 1994.

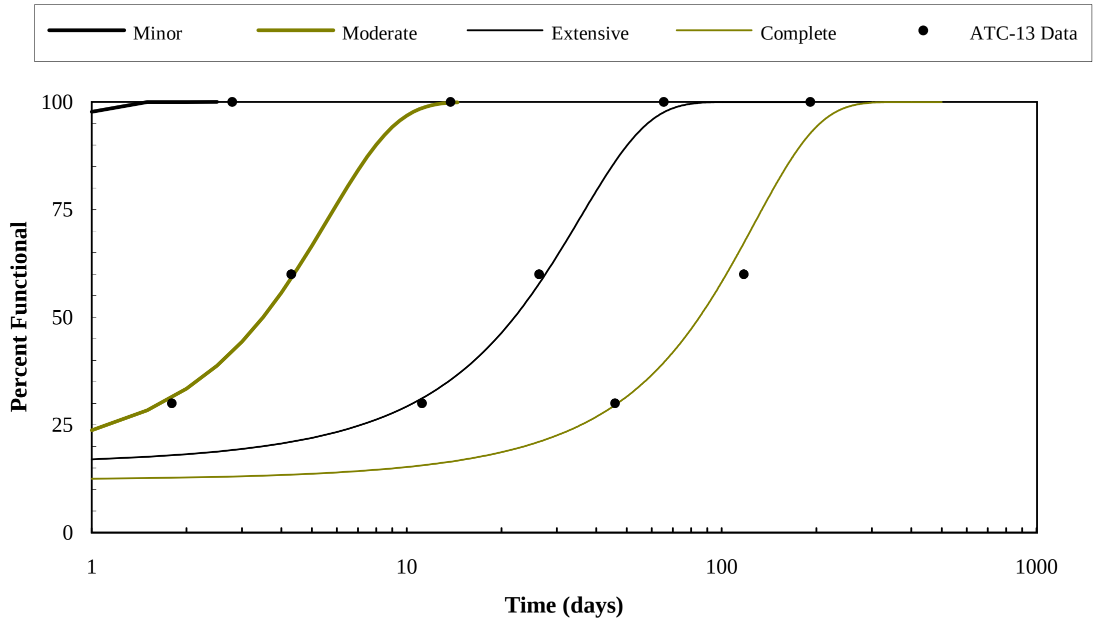


Figure 7.23 Restoration Curves for Port Waterfront Structures.

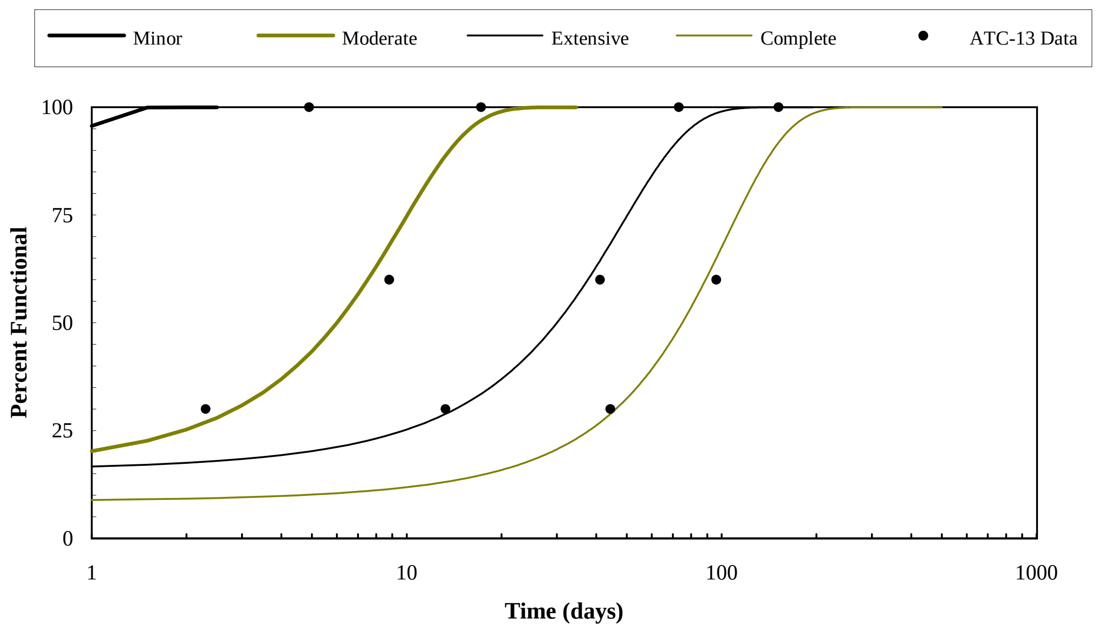


Figure 7.24 Restoration Curves for Cranes/Cargo Handling Equipment.

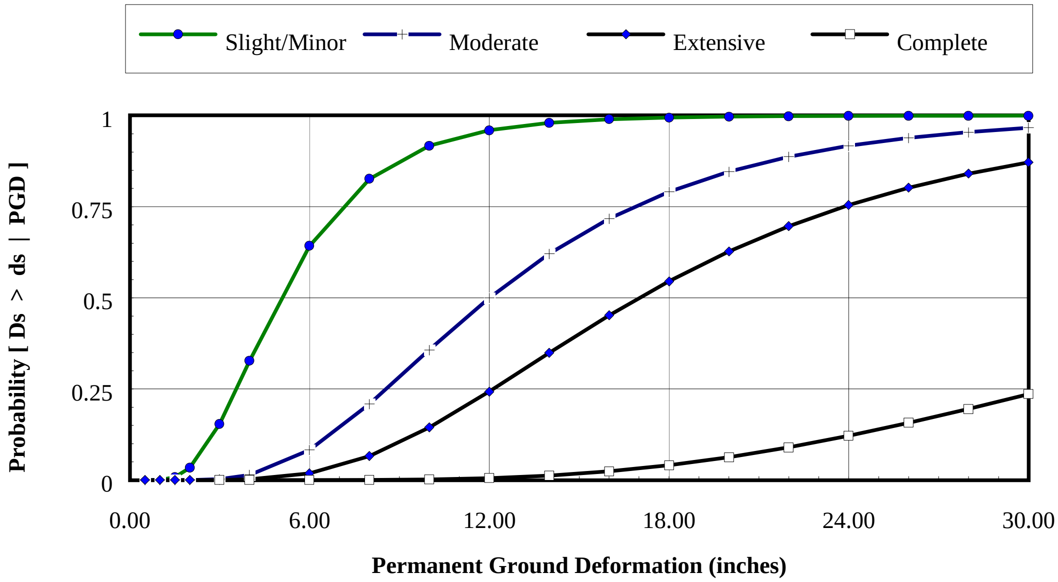


Figure 7.25 Fragility Curves for Waterfront Structures.

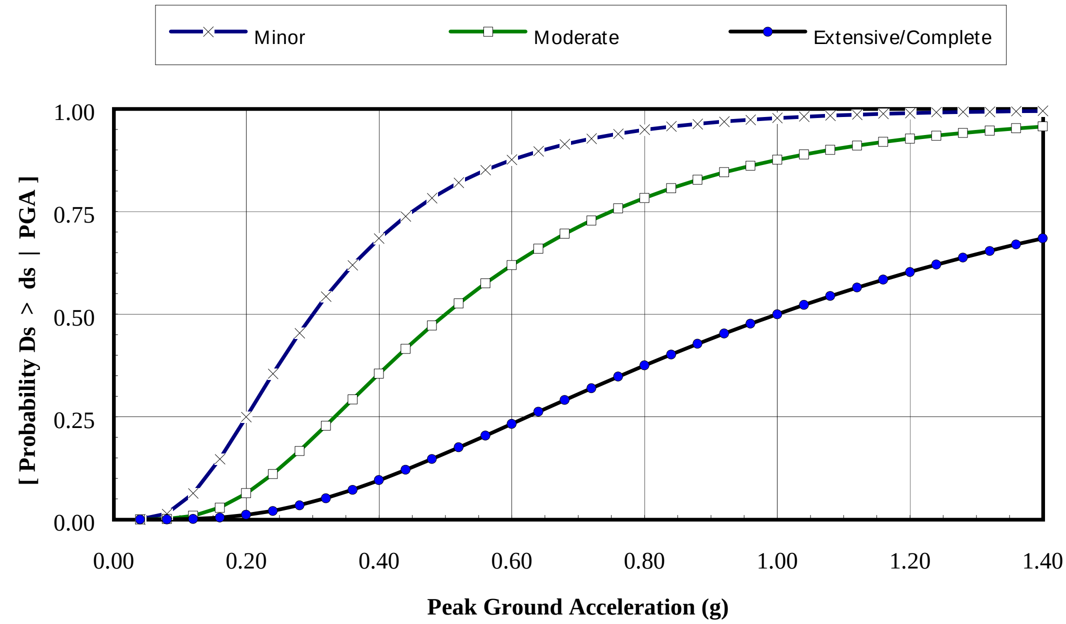


Figure 7.26 Fragility Curves for Stationary Cranes/Cargo Handling Equipment Subject to Peak Ground Acceleration.

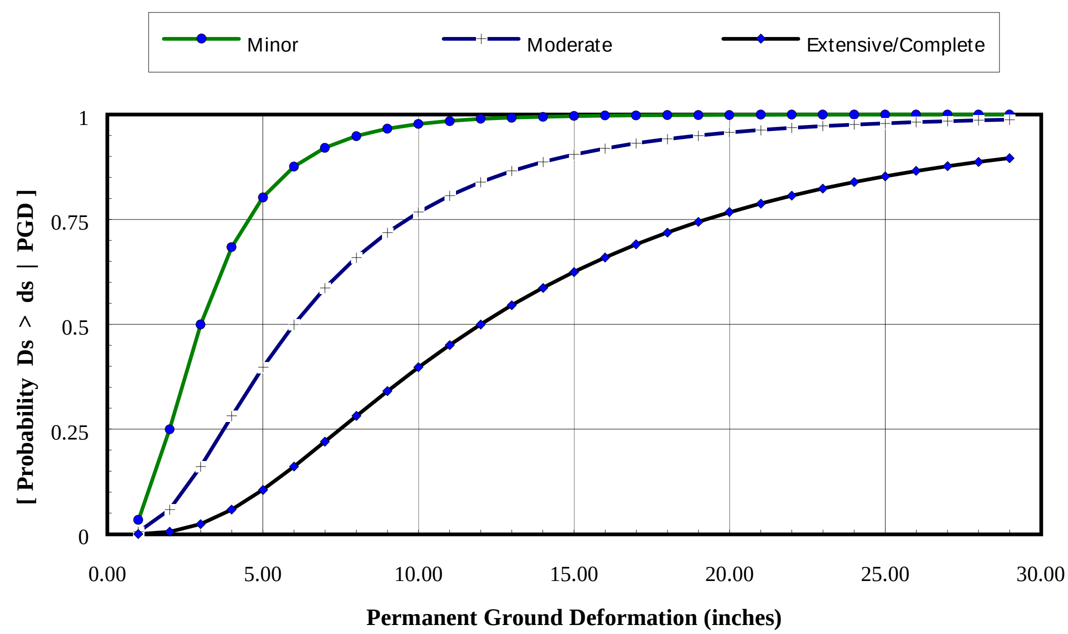


Figure 7.27 Fragility Curves for Stationary Cranes/Cargo Handling Equipment Subject to Permanent Ground Deformation.

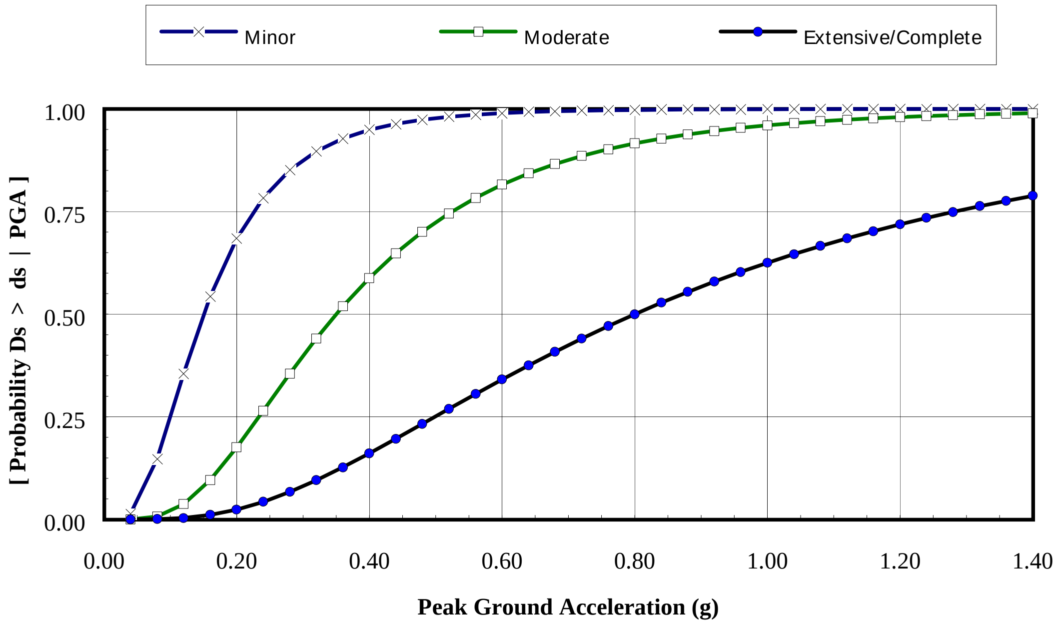


Figure 7.28 Fragility Curves for Rail Mounted Cranes/Cargo Handling Equipment Subject to Peak Ground Acceleration.

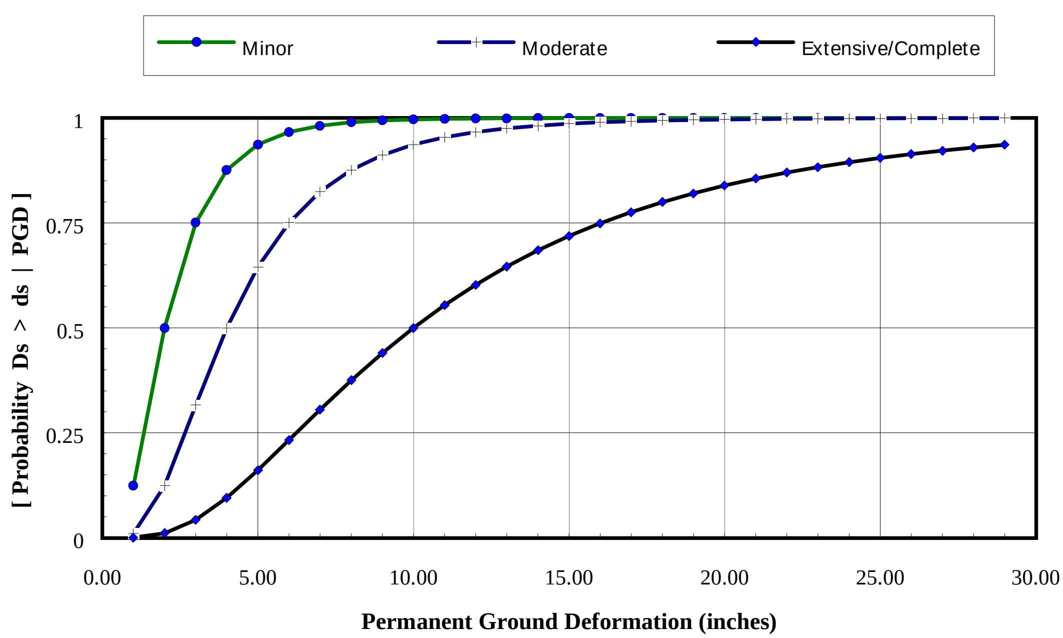


Figure 7.29 Fragility Curves for Rail Mounted Cranes/Cargo Handling Equipment Subject to Permanent Ground Deformation.

7.6 Ferry Transportation System

7.6.1 Introduction

This section presents a loss estimation methodology for a ferry transportation system. Ferry systems consist of waterfront structures (e.g., wharf, piers and seawalls); fuel, maintenance, and dispatch facilities; and passenger terminals.

The waterfront structures are located at the points of embarkation or disembarkation, and they are similar to, although not as extensive as, those of the port transportation system. In some cases the ferry system may be located within the boundary of the port transportation system. The points of embarkation or disembarkation are located some distance apart from one another, usually on opposite shorelines.

Fuel and maintenance facilities are usually located at one of these two points. The size of the fuel facility is smaller than that of the port facility. In many cases, the dispatch facility is located in the maintenance facility or one of the passenger terminals.

7.6.2 Scope

The scope of this section includes development of methods for estimation of earthquake damage to a ferry transportation system given knowledge of components (i.e., waterfront structures; fuel, maintenance, and dispatch facilities; and passenger terminals), classification (i.e. for fuel facilities, anchored or unanchored components, with or without back-up power), and the ground motion (i.e. peak ground acceleration and/or permanent ground deformation).

Damage states describing the level of damage to each of the ferry system components are defined (i.e. slight/minor, moderate, extensive or complete). Damage states are related to damage ratio (defined as ratio of repair to replacement cost) for evaluation of direct economic loss. Component restoration curves are provided for each damage state to evaluate loss of function. Restoration curves describe the fraction or percentage of the component that is expected to be open or operational as a function of time following the earthquake. For ferries the restoration is dependent upon the extent of damage to the waterfront structures; fuel, maintenance, and dispatch facilities; and passenger terminals.

Fragility curves are developed for each class of the ferry system components. These curves describe the probability of reaching or exceeding each damage state given the level of ground motion. Based on these fragility curves, a method for assessing functionality of each of the five ferry system components is presented.

Interdependence of components on overall system functionality is not addressed by the methodology. Such considerations require a system (network) analysis that would be performed separately by a transportation system expert as an advanced study.

7.6.3 Input Requirements and Output Information

Required input to estimate damage to ferry systems includes the following items:

Ferry Waterfront Structures
- Geographic locations of harbor
- PGA & PGD

Ferry Fuel Facilities
- Geographical location of facility
- PGA and PGD
- Classification

Ferry Maintenance Facilities
- Geographical location of facility
- Spectral values and PGD
- Classification (i.e. building type)

Ferry Dispatch Facilities
- Geographical location of facility
- PGA and PGD
- Classification

Ferry Terminal Buildings
- Geographical location of building
- Spectral values and PGD
- Classification (i.e. building type)

Direct damage output for ferry systems includes probability estimates of (1) component functionality and (2) physical damage, expressed in terms of the component's damage ratio. Damage ratios are used as inputs to direct economic loss methods, as described in section 15.3 of Chapter 15.

7.6.4 Form of Damage Functions

Damage functions or fragility curves for all five ferry system components mentioned above, are lognormal functions that give the probability of reaching or exceeding different levels of damage for a given level of ground motion. Each fragility curve is characterized by a median value of ground motion (or failure) and an associated dispersion factor (lognormal standard deviation). Ground motion is quantified in terms of peak ground acceleration (PGA) and ground failure is quantified in terms of permanent ground displacement (PGD).

- For waterfront structures, the fragility curves are defined in terms of PGA & PGD.

- For fuel facilities, maintenance and dispatch facilities; and terminal building, the fragility curves are defined in terms of PGA and PGD.

Definitions of various damage states and the methodology used in deriving fragility curves for ferry system components are presented in the following subsections.

7.6.5 Description of Ferry System Components

A ferry system consists of the five components mentioned above: waterfront structures, fuel facilities, maintenance facilities, dispatch facilities, and passenger terminals. This section provides a brief description of each.

Waterfront Structures
These are the same as those for port systems described in Section 7.5.5.

Fuel Facilities
These facilities are similar to those for port system mentioned in Section 7.5.5.

Maintenance Facilities
These are often steel braced frame structures, but other building types are possible.

Dispatch Facilities
These are similar to those defined for railway system in Section 7.2.5.

Passenger Terminals
These are often moment resisting steel frames, but other building types are possible.

7.6.6 Definitions of Damage States

A total of five damage states are defined for ferry system components. These are none (ds_1), slight/minor (ds_2), moderate (ds_3), extensive (ds_4) and complete (ds_5).

Slight/Minor Damage (ds_2)

- For waterfront structures, ds_2 is the same as that for waterfront structures in the port module.

- For fuel facilities, ds_2 is the same as that for fuel facilities in the port module.

- For maintenance facilities, ds_2 is defined by slight damage to building.

- For dispatch facilities, ds_2 is the same as that for dispatch facilities in the railway module.
- For passenger terminals, ds_2 is defined by slight damage to building.

Moderate Damage (ds_3)

- For waterfront structures, ds_3 is the same as that for waterfront structures in the port module.
- For fuel facilities, ds_3 is the same as that for fuel facilities in the port module.
- For maintenance facilities, ds_3 is defined by moderate damage to building.
- For dispatch facilities, ds_3 is the same as that for dispatch facilities in the railway module.
- For passenger terminals, ds_3 is defined by moderate damage to building.

Extensive Damage (ds_4)

- For waterfront structures, ds_4 is the same as that for waterfront structures in the port module.
- For fuel facilities, ds_4 is the same as that for fuel facilities in the port module.
- For maintenance facilities, ds_4 is defined by extensive damage to building.
- For dispatch facilities, ds_4 is the same as that for dispatch facilities in the railway module.
- For passenger terminals, ds_4 is defined by extensive damage to building.

Complete Damage (ds_5)

- For waterfront structures, ds_5 is the same as that for waterfront structures in the port module.
- For fuel facilities, ds_5 is the same as that for fuel facilities in the port module.
- For maintenance facilities, ds_5 is defined by complete damage to building.

- For dispatch facilities, ds_5 is the same as that for dispatch facilities in the railway module.
- For passenger terminals, ds_5 is defined as complete damage to building.

7.6.7 Component Restoration Curves

Ferry systems are made of components that are similar to either those in port systems (i.e. waterfront structures, fuel facilities), or those in railway systems (i.e. dispatch facilities, maintenance facilities, passenger terminals). Therefore, restoration curves for ferry system components can be found in either Section 7.5 or Section 7.2.

7.6.8 Development of Damage Functions

Similar to restoration curves, damage functions for ferry system components can be found in either Section 7.5 or Section 7.2.

7.6.9 Guidance for Loss Estimation Using Advanced Data and Models Analysis

For this type of analysis, the expert can use the methodology developed with the flexibility to: (1) include a refined inventory of the ferry system pertaining to the area of study, and (2) include component specific and system specific fragility data. Default User-Supplied Data Analysis damage algorithms can be modified or replaced to accommodate any specified key component of a ferry system, such as a maintenance facility. Similarly, better restoration curves could be developed given knowledge of available resources and a more accurate layout of the ferry transportation network within the local topographic and geological conditions.

7.6.10 References

Applied Technology Council, "Earthquake Damage Evaluation Data for California", ATC-13, Redwood City, CA, 1985.

G & E Engineering Systems, Inc. (G & E), "NIBS Earthquake Loss Estimation Methods, Technical Manual, Transportation Systems", May 1994.

7.7 Airport Transportation System

7.7.1 Introduction

This section presents a loss estimation methodology for an airport transportation system. Airport transportation system consists of runways, control tower, fuel facilities, terminal buildings, maintenance facilities, hangar facilities, and parking structures. For airports, control towers are often constructed of reinforced concrete, while terminal buildings and maintenance facilities are often constructed of structural steel or reinforced concrete. Fuel facilities are similar to those for railway transportation systems.

7.7.2 Scope

The scope of this section includes development of methods for estimation of earthquake damage to an airport transportation system given knowledge of components (i.e. runways, control tower, fuel, and maintenance facilities, terminal buildings, and parking structures), classification, and ground motion (i.e. peak ground acceleration and/or permanent ground deformation).

Damage states describing the level of damage to each of the airport system components are defined (i.e. slight, moderate, extensive or complete). Damage states are related to damage ratio (defined as ratio of repair to replacement cost) for evaluation of direct economic loss. Component restoration curves are provided for each damage state to evaluate loss of function. Restoration curves describe the fraction or percentage of the component that is expected to be open or operational as a function of time following the earthquake. For airports, the restoration is dependent upon the extent of damage to the airport terminals, buildings, storage tanks (for fuel facilities), control tower, and runways.

Fragility curves are developed for each component class of the airport system. These curves describe the probability of reaching or exceeding each damage state given the level of ground motion. Based on these fragility curves, a method for assessing functionality of each of the six airport system components is presented.

7.7.3 Input Requirements and Output Information

Required input to estimate damage to airport systems includes the following items:

Runways

- Geographic location of airport [longitude and latitude]
- PGD

Control Tower

- Geographic location of airport [longitude and latitude]
- PGA and PGD

- Classification (i.e. building type)

Fuel Facilities

- Geographical location of facility [longitude and latitude]
- PGA and PGD
- Classification

Terminal Buildings

- Geographical location of airport [longitude and latitude]
- Spectral values and PGD
- Classification (i.e. building type)

Maintenance and Hangar Facilities

- Geographical location of facility [longitude and latitude]
- Spectral values and PGD
- Classification (i.e. building type)

Parking Structures

- Geographical location of structure [longitude and latitude]
- Spectral values and PGD
- Classification (i.e. building type)

Direct damage output for airport systems includes probability estimates of (1) component functionality and (2) physical damage, expressed in terms of the component's damage ratio. Damage ratios are used as inputs to direct economic loss methods, as described in section 15.3 of Chapter 15.

7.7.4 Form of Damage Functions

Damage functions or fragility curves for all five airport system components mentioned above, are lognormal functions that give the probability of reaching or exceeding different levels of damage for a given level of ground motion. Each fragility curve is characterized by a median value of ground motion (or failure) and an associated dispersion factor (lognormal standard deviation). Ground motion is quantified in terms of peak ground acceleration (PGA) and ground failure is quantified in terms of permanent ground displacement (PGD).

- For runways, the fragility curves are defined in terms of PGD.

- For control towers, the fragility curves are defined in terms of Spectral values and PGD.

- For all other facilities, the fragility curves are defined in terms of Spectral values and PGD.

Definitions of various damage states and the methodology used in deriving these fragility curves are presented in the following section.

7.7.5 Description of Airport Components

An airport system consists of the six components mentioned above: runways, control tower, fuel facilities, maintenance facilities, and parking structures. This section provides a brief description of each.

Runways
This component consists of well-paved "flat and wide surfaces".

Control Tower
Control tower consists of a building and the necessary equipment of air control and monitoring.

Fuel Facilities
These have been previously defined in Section 7.2.5 of railway systems.

Terminal Buildings
These are similar to urban stations of railway systems from the classification standpoint (as well as services provided to passengers).

Maintenance Facilities, Hangar Facilities, and Parking Structures
Classification of maintenance facilities is the same as for those in railway systems. Hangar facilities and parking structures are mainly composed of buildings.

7.7.6 Definitions of Damage States

A total of five damage states are defined for airport system components. These are none (ds_1), slight/minor (ds_2), moderate (ds_3), extensive (ds_4) and complete (ds_5).

Slight/Minor Damage (ds_2)

- For runways, ds_2 is defined as minor ground settlement or heaving of runway surface.
- For control tower, ds_2 is defined as slight damage to the building as given in section 5.3.
- For fuel facilities, ds_2 is the same as that for fuel facilities in the railway module.

- For terminal buildings, ds_2 is defined as slight damage to the building as given in section 5.3.
- For maintenance and hangar facilities, ds_2 is defined as slight damage to the building as given in section 5.3.
- For parking structures, ds_2 is defined as slight damage to the building as given in section 5.3.

Moderate Damage (ds_3)

- For runways, ds_3 is defined same as ds_2.
- For control tower, ds_3 is defined as moderate damage to the building as given in section 5.3.
- For fuel facilities, ds_3 is the same as that for fuel facilities in the railway module.
- For terminal buildings, ds_3 is defined as moderate damage to the building as given in section 5.3.
- For maintenance and hangar facilities, ds_3 is defined as moderate damage to the building as given in section 5.3.
- For parking structures, ds_3 is defined as moderate damage to the building as given in section 5.3.

Extensive Damage (ds_4)

- For runways, ds_4 is defined as considerable ground settlement or considerable heaving of runway surface.
- For control tower, ds_4 is defined as extensive damage to the building as given in section 5.3.
- For fuel facilities, ds_4 is the same as that for fuel facilities in the railway module.
- For terminal buildings, ds_4 is defined as extensive damage to the building as given in section 5.3.
- For maintenance and hangar facilities, ds_4 is defined as extensive damage to the building as given in section 5.3.

- <u>For parking structures</u>, ds_4 is defined as extensive damage to the building as given in section 5.3.

<u>Complete Damage</u> (ds_5)

- <u>For runways</u>, ds_5 is defined as extensive ground settlement or excessive heaving of runway surface.
- <u>For control tower</u>, ds_5 is defined as complete damage to the building as given in section 5.3.
- <u>For fuel facilities</u>, ds_5 is the same as that for fuel facilities in the railway module.
- <u>For terminal buildings</u>, ds_5 is defined as complete damage to the building as given in section 5.3.
- <u>For maintenance and hangar facilities</u>, ds_5 is defined as complete damage to the building as given in section 5.3.
- <u>For parking structures</u>, ds_5 is defined as complete damage to the building as given in section 5.3.

7.7.7 Component Restoration Curves

Restoration Curves are developed based on a best fit to ATC-13 data for social functions SF 27.a and SF 27.b, consistent with damage states defined in the previous section. Normal distribution functions are developed using this ATC-13 data for the mean time for 30%, 60% and 100% restoration. Means and dispersions of these restoration functions are given in Table 7.16.a and shown in Figures 7.30 and 7.31. The discretized restoration functions are presented in Table 7.16.b, where the percentage restoration is shown at selected time intervals.

Table 7.16.a Restoration Functions for Airport Components

Restoration Functions (All Normal Distributions)			
Classification	**Damage State**	**Mean (Days)**	**σ**
Control Towers, Parking Structures, Hangar Facilities, Terminal Building	slight	0	0
	moderate	1.5	1.5
	extensive	50	50
	complete	150	120
Runways	slight/moderate	2.5	2.5
	extensive	35	35
	complete	85	65

Table 7.16.b Discretized Restoration Functions for Aiport Sub-Components

Discretized Restoration Functions						
Classification	**Damage State**	**1 day**	**3 days**	**7 days**	**30 days**	**90 days**
Control Towers, Parking Structures, Hangar Facilities, Terminal Building	slight	100	100	100	100	100
	moderate	37	84	100	100	100
	extensive	16	17	20	34	79
	complete	11	11	12	16	31
Runways	slight/moderate	27	57	100	100	100
	extensive	17	18	21	44	95
	complete	10	11	12	20	53

7.7.8 Development of Damage Functions

Damage functions for airport system facilities are defined in terms of PGA and PGD except for runways (PGD only). Note that, unless it is specified otherwise, ground failure (PGD) related damage functions for these facilities are assumed to be similar to those described for railroad system facilities in section 7.2.8.

An example of how to combine PGD and PGA algorithms is presented in section 7.2.8.

Damage Functions for Runways

The earthquake hazard for airport runways is ground failure. Little damage is attributed to ground shaking; therefore, the damage function includes only ground failure as the hazard. All runways are assumed to be paved. The median values and dispersion for the damage states for runways are given in Table 7.17. These damage functions are also shown in Figure 7.32.

Table 7.17 Damage Algorithms for Runways

Permanent Ground Deformation			
Classification	**Damage State**	**Median (in)**	**β**
Runways	slight/moderate	1	0.6
	extensive	4	0.6
	complete	12	0.6

Damage Functions for Rest of Airport System Components

In section 7.7.5, these components were defined by "one to one" correspondence with those for railway systems. Therefore, damage functions for the remaining airport components (i.e. fuel facilities, maintenance facilities, and other buildings) can be found in Section 7.2.8.

7.7.9 Guidance for Loss Estimation Using Advanced Data and Models Analysis

For this level of analysis, the expert can use the methodology developed with the flexibility to: (1) include a refined inventory of the airport system pertaining to the area of study, and (2) include component specific and system specific fragility data. Default User-Supplied Data Analysis damage algorithms can be modified or replaced to accommodate any specified key component of a airport system, such as a control tower. Similarly, better restoration curves could be developed given knowledge of available resources and a more accurate layout of the transportation network within the local topographic and geological conditions.

7.7.10 References

Applied Technology Council, "Earthquake Damage Evaluation Data for California", ATC-13, Redwood City, CA, 1985.

G & E Engineering Systems, Inc. (G & E), "NIBS Earthquake Loss Estimation Methods, Technical Manual, Transportation Systems (Airport Systems)", May 1994.

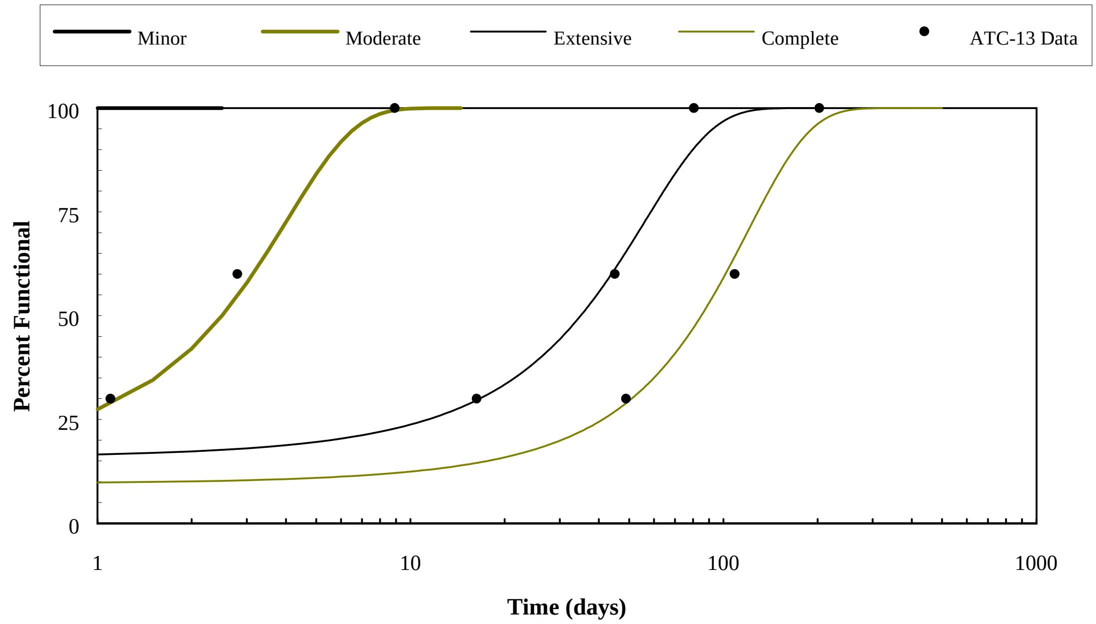


Figure 7.30 Restoration Curve for Airport Runways.

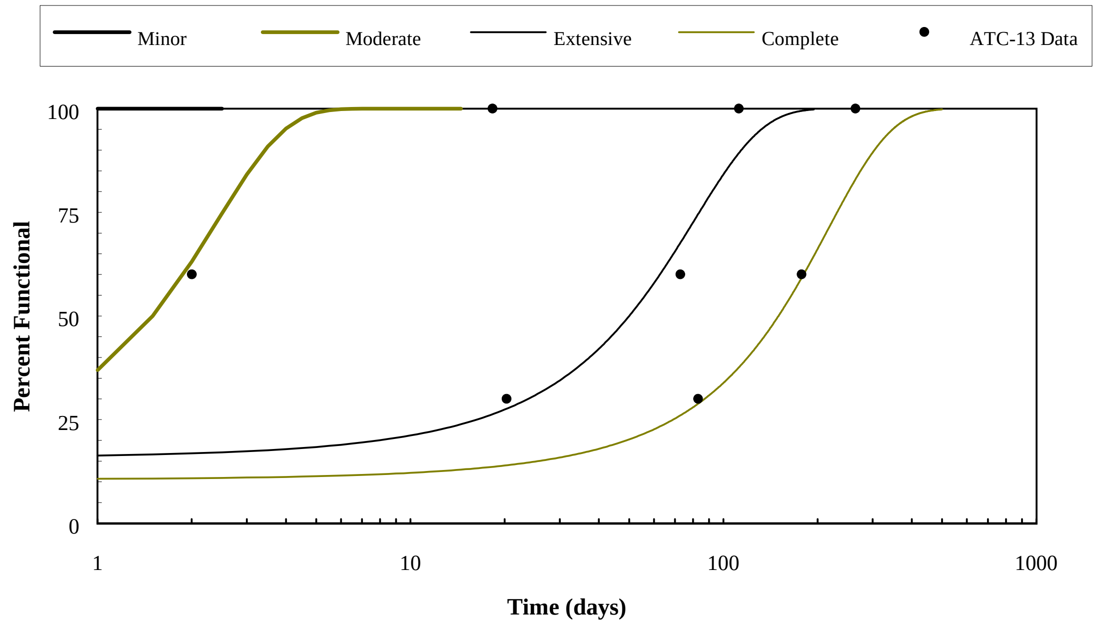


Figure 7.31 Restoration Curves for Airport Buildings, Facilities, and Control Tower.

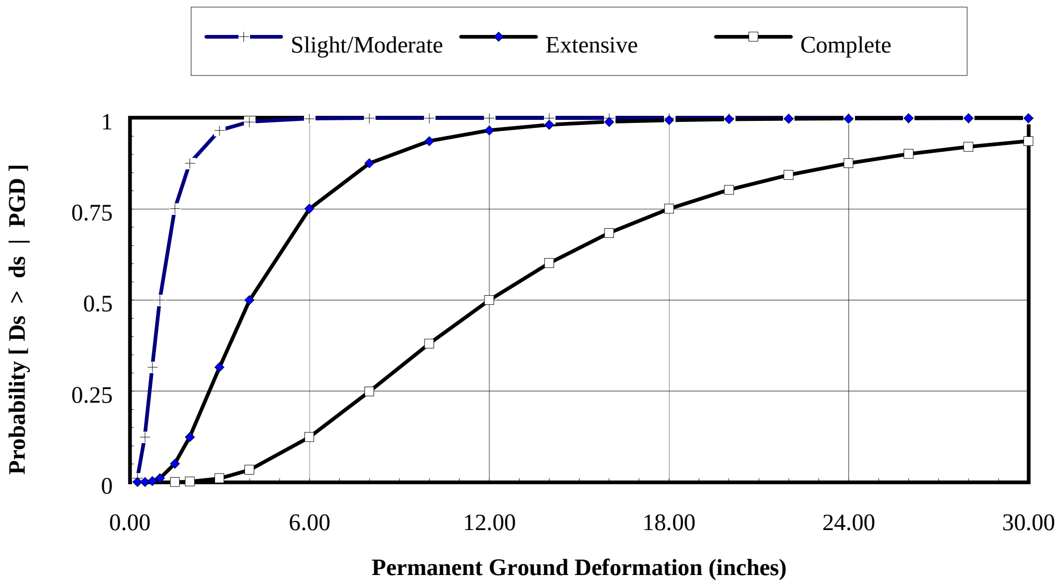


Figure 7.32 Fragility Curves for Runways Subject to Permanent Ground Deformation at Various Damage States.

APPENDIX 7A

Any given subcomponent in the lifeline methodology can experience all five damage states; however, the only damage states listed in the appendices of Chapters 7 and 8 are the ones used in the fault tree logic of the damage state of interest of the component.

Table A.7.1 Subcomponent Damage Algorithms: Rock Tunnels (after G&E, 1994)

Peak Ground Acceleration			
Subcomponents	Damage State	Median (g)	β
Liner	slight moderate	0.6 0.8	0.4 0.6

Permanent Ground Deformation			
Subcomponents	Damage State	Median (in)	β
Liner	slight extensive complete	6 12 60	0.7 0.5 0.5
Portal	slight extensive complete	6 12 60	0.7 0.5 0.5

Table A.7.2 Subcomponent Damage Algorithms: Cut & Cover Tunnels (after G&E, 1994)

Peak Ground Acceleration			
Subcomponents	Damage State	Median (g)	β
Liner	slight moderate	0.5 0.7	0.4 0.6

Permanent Ground Deformation			
Subcomponents	Damage State	Median (in)	β
Liner	slight extensive complete	6 12 60	0.7 0.5 0.5
Portal	slight extensive complete	6 12 60	0.7 0.5 0.5

APPENDIX 7B

Table B.7.1 Subcomponent Damage Algorithms: Seismically Designed Railway Bridges (after G&E, 1994)

Peak Ground Acceleration			
Subcomponents	**Damage State**	**Median (g)**	**β**
Column	slight extensive complete	0.45 1.0 1.4	0.55 0.7 0.7
Abutment	slight moderate	0.45 1.0	0.55 0.7
Connection	moderate extensive	0.86 1.4	0.70 0.70
Deck	slight	0.67	0.55

Permanent Ground Deformation			
Subcomponents	**Damage State**	**Median (in)**	**β**
Column	extensive complete	14 28	0.7 0.7
Abutment	moderate extensive	15 30	0.7 0.7
Connection	complete	30	0.7
Approach	slight moderate extensive	2 12 24	0.5 0.7 0.7

Table B.7.2 Subcomponent Damage Algorithms: Conventionally Designed Railway Bridges (after G&E, 1994)

Peak Ground Acceleration			
Subcomponents	**Damage State**	**Median (g)**	**β**
Column	slight extensive complete	0.3 0.8 1.0	0.55 0.7 0.7
Abutment	slight moderate	0.3 0.8	0.55 0.7
Connection	moderate extensive	0.7 1.0	0.70 0.70
Deck	slight	0.5	0.55

Permanent Ground Deformation			
Subcomponents	**Damage State**	**Median (in)**	**β**
Column	extensive complete	10 21	0.7 0.7
Abutment	moderate extensive	10 21	0.7 0.7
Connection	complete	21	0.7
Approach	slight moderate extensive	2 12 24	0.5 0.7 0.7

Table B.7.3 Subcomponent Damage Algorithms:
Fuel Facility with Anchored Components (after G&E, 1994)

Peak Ground Acceleration			
Subcomponents	**Damage State**	**Median (g)**	**β**
Electric Power (Backup)	slight moderate	0.80 1.00	0.60 0.80
Electric Power (Off-Site)	slight moderate	0.15 0.25	0.6 0.5
Tank	slight moderate extensive complete	0.30 0.70 1.25 1.60	0.60 0.60 0.65 0.60
Pump Building	slight moderate extensive complete	0.15 0.40 0.80 1.50	0.80 0.80 0.80 0.80
Horizontal Pump	extensive	1.60	0.60
Equipment	moderate	1.00	0.60

Table B.7.4 Subcomponent Damage Algorithms:
Fuel Facility with Unanchored Components (after G&E, 1994)

Peak Ground Acceleration			
Subcomponents	**Damage State**	**Median (g)**	**β**
Electric Power (Backup)	slight moderate	0.20 0.40	0.60 0.80
Electric Power (Off-Site)	slight moderate	0.15 0.25	0.6 0.5
Tank	slight moderate extensive complete	0.15 0.35 0.68 0.95	0.70 0.75 0.75 0.70
Pump Building	slight moderate extensive complete	0.15 0.40 0.80 1.50	0.80 0.80 0.80 0.80
Horizontal Pump	extensive	1.60	0.60
Equipment	moderate	0.60	0.60

Table B.7.5 Subcomponent Damage Algorithms: Dispatch Facility with Anchored Components (after G&E, 1994)

Peak Ground Acceleration			
Subcomponents	**Damage State**	**Median (g)**	**β**
Electric Power (Backup)	slight moderate	0.80 1.00	0.60 0.80
Electric Power (Off-Site)	slight moderate	0.15 0.25	0.6 0.5
Building	slight moderate extensive complete	0.15 0.40 0.80 1.50	0.80 0.80 0.80 0.80
Equipment	moderate	1.00	0.60

Table B.7.6 Subcomponent Damage Algorithms: Dispatch Facility with Unanchored Components (after G&E, 1994)

Peak Ground Acceleration			
Subcomponents	**Damage State**	**Median (g)**	**β**
Electric Power (Backup)	slight moderate	0.20 0.40	0.60 0.80
Electric Power (Off-Site)	slight moderate	0.15 0.25	0.6 0.5
Building	slight moderate extensive complete	0.15 0.40 0.80 1.50	0.80 0.80 0.80 0.80
Equipment	moderate	0.60	0.60

APPENDIX 7C

Table C.7.1 Subcomponent Damage Algorithms for DC Power Substation with Anchored Components

Peak Ground Acceleration			
Subcomponents	Damage State	Median (g)	β
Building	slight moderate extensive complete	0.15 0.40 0.80 1.50	0.80 0.80 0.80 0.80
Equipment	moderate	1.00	0.60
Off-Site Power	slight moderate	0.15 0.25	0.6 0.5

Table C.7.2 Subcomponent Damage Algorithms for DC Power Substation with Unanchored Components

Peak Ground Acceleration			
Subcomponents	Damage State	Median (g)	β
Building	slight moderate extensive complete	0.15 0.40 0.80 1.50	0.80 0.80 0.80 0.80
Equipment	moderate	0.60	0.60
Off-Site Power	slight moderate	0.15 0.25	0.6 0.5

APPENDIX 7D

Table 7.D.1 Subcomponent Damage Algorithms for Waterfront Structures

Permanent Ground Deformation			
Subcomponents	**Damage State**	**Median (in)**	**β**
Wharf	slight	8	0.6
Piers	slight	8	0.6
	moderate	16	0.6
	extensive	24	0.6
	complete	60	0.6
Seawalls	slight	8	0.6
	moderate	16	0.6
	extensive	24	0.6
	complete	60	0.6

Chapter 8
Direct Damage to Lifelines - Utility Systems

This chapter describes and presents the methodology for estimating direct damage to Utility Systems. The Utility Module is composed of the following six systems:

- Potable Water
- Waste Water
- Oil (crude and refined)
- Natural Gas
- Electric Power
- Communication

The flowchart of the overall methodology, highlighting the utility system module and its relationship to other modules, is shown in Flowchart 8.1.

8.1 Potable Water Systems

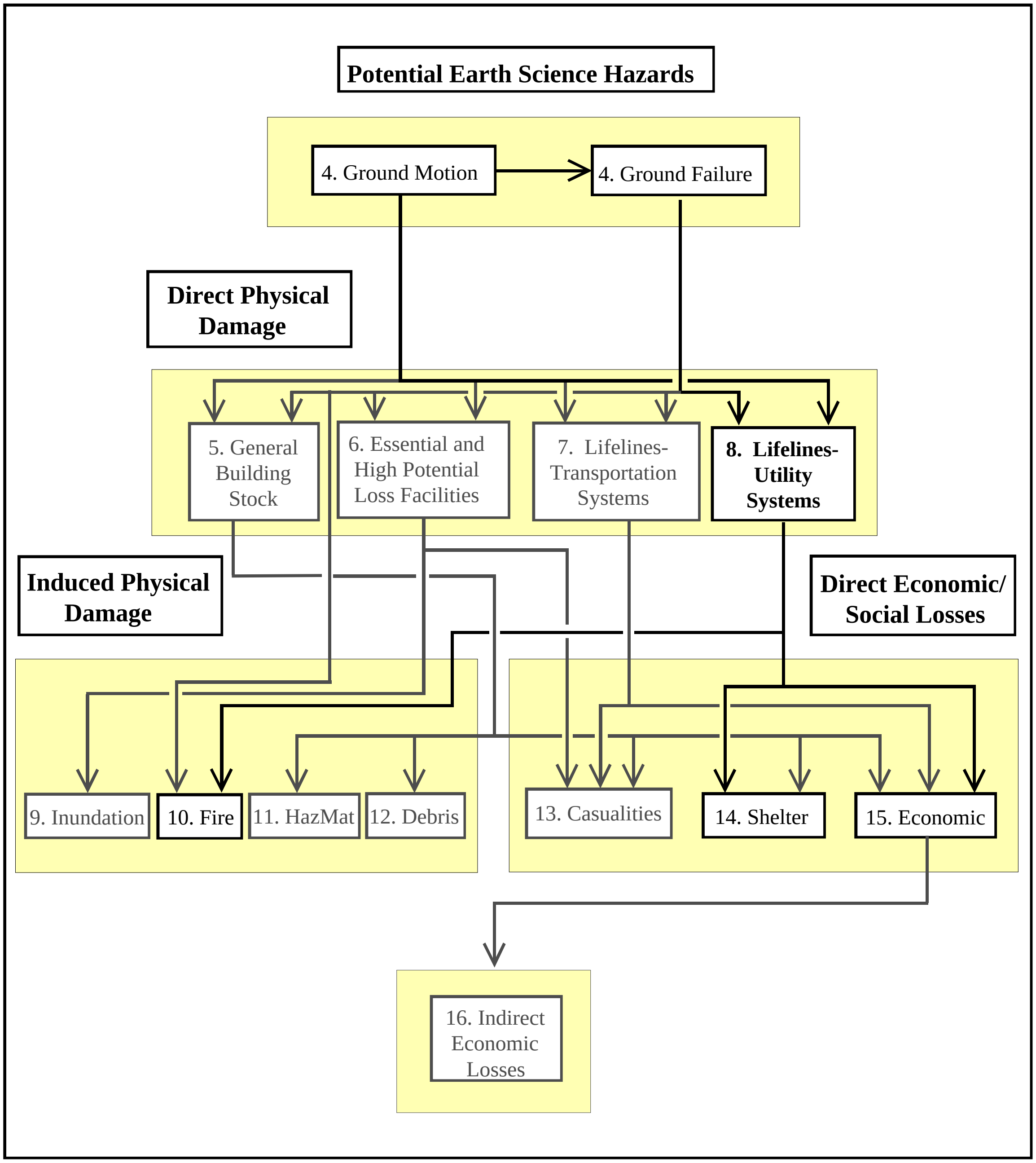
8.1.1 Introduction

This section presents a loss estimation methodology for a water system during earthquakes. This system consists of supply, storage, transmission, and distribution components. All of these components are vulnerable to damage during earthquakes, which may result in a significant disrutpion to the water utility network.

8.1.2 Scope

The scope of this section includes development of methods for estimation of earthquake damage to a potable water system given knowledge of the system's components (i.e., tanks, aqueducts, water treatment plants, wells, pumping stations, conveyance pipes, junctions, hydrants, and valves), classification (i.e., for water treatment plants, small, medium or large), and the ground motion (i.e. peak ground velocity, peak ground acceleration and/or permanent ground deformation). Damage states describing the level of damage to each of the water system components are defined (i.e., slight/minor, moderate, extensive, or complete), while for pipelines, the number of repairs/km is the key paramter. Fragility curves are developed for each classification of the water system component. These curves describe the probability of reaching or exceeding each damage state given the level of ground motion or ground failure.

Based on these fragility curves, a method for assessing functionality of each component of the water system is presented. A simplified approach for evaluating the overall water system network performance is also provided.



Flowchart 8.1 Utility System Damage Relationship to Other Modules of the Earthquake Loss Estimation Methodology

8.1.3 Input Requirements and Output Information

Depending on the desired level of analysis, the input required for analyzing water systems varies. In total, three levels of analysis are enabled in Hazus.

Level One:

The default inventory in Hazus contains estimate of potable water pipelines aggregated at the census tract level. This pipeline data was developed using the US Census TIGER street file datasets. For the level one analysis, eighty (80) percent of the pipes are assumed to be brittle with the remaining pipes assumed to be ductile. In addition, peak ground velocity and permanent ground deformation (PGV and PGD) for each census tract is needed for the analysis.

The results from a level one analysis include the expected number of leaks and breaks per census tract and a simplified evaluation of the potable water system network performance (i.e. number of households without water).

Level Two:

For this level, the input required to estimate damage to potable water systems includes the following items:

Transmission Aqueducts and Distribution Pipelines

- Geographical location of aqueduct/pipe links (longitude and latitude of end nodes)
- Peak ground velocity and permanent ground deformation (PGV and PGD)
- Classification (ductile pipe or brittle pipe)

Reservoirs, Water Treatment Plants, Wells, Pumping Stations and Storage Tanks

- Geographical location of facility (longitude and latitude)
- PGA and PGD
- Classification (e.g., capacity and anchorage)

Direct damage output from level 2 analysis includes probability estimates of (1) component functionality and (2) damage, expressed in terms of the component's damage ratio (repair cost to replacement cost). Note that damage ratios for each of the potable water system components are presented in section 15.3 of Chapter 15. In addition, a simplified evaluation of the potable water system network performance is also provided. This is based on network analyses done for Oakland, San Francisco and Tokyo. The output from this simplified version of network analysis consists of an estimate of the flow reduction to the areas served by the water system being evaluated. Details of this methodology are presented in subsection 8.1.9.

<u>Level Two Enhanced</u>:
This level of analysis essentially relies on the same type of information provided in the previous level with <u>four</u> main differences:

- Three additional components are considered. These are: junctions, hydrants, and valves.
- Connectivity of the components is maintained (i.e., what facilities are connected to which pipeline links or valves).
- Serviceability in the system considered (i.e., the demand pressures and flow demands at the different distribution nodes).
- Input data for the water system need to be in one of the following three commercially available formats: KYPIPE, EPANET, or CYBERNET.

Recent work by Khater and Waisman (EQE, 1999) elaborates in great details on the level two enhanced analysis model implemented in **Hazus®**. In particular, this work provides a comprehensive theoretical background on the governing equations for a water system and explains how the commercial data need to be formatted in order to be able to import it into **Hazus®**. This work is available in a separate document entitled "Potable Water System Analysis Model (POWSAM)" that can be acquired directly from NIBS.

Results from the level two enhanced analysis are similar to the level two. That is, probability estimates of (1) component functionality and (2) damage, expressed in terms of the component's damage ratio (repair cost to replacement cost). The main difference is in the evaluation of the potable water system network performance, which is in this case based on a more comprehensive approach. Note that in either case, the performance is expressed in terms of an estimate of the flow reduction to the areas served by the water system being evaluated and the number of households expected to be deprived from water.

8.1.4 Form of Damage Functions

Damage functions or fragility curves for water system components other than pipelines are modeled as lognormally-distributed functions that give the probability of reaching or exceeding different damage states for a given level of ground motion (quantified in terms of PGA) and ground failure (quantified in terms of PGD). Each of these fragility curves is characterized by a median value of ground motion (or failure) and an associated dispersion factor (lognormal standard deviation). For pipelines, empirical relations that give the expected repair rates due to ground motion (quantified in terms of PGV) or ground failure (quantified in terms of PGD) are provided. Definitions of various damage states and the methodology used in deriving all these fragility curves are presented in the next section.

8.1.5 Description of Potable Water System Components

A potable water system typically consists of terminal reservoirs, water treatment plants, wells, pumping plants, storage tanks and transmision and distribution pipelines. In this subsection, a brief description of each of these components is presented.

Terminal Reservoirs

Terminal reservoirs are typically lakes (man made or natural) and are usually located nearby and upstream of the water treatment plant. Vulnerability of terminal reservoirs and associated dams is marginally assessed in the loss estimation methodology. Therefore, even though reservoirs are an essential part of a potable water system, it is assumed in the analysis of water systems that the amount of water flowing into water treatment plants from reservoirs right after an earthquake is essentially the same as before the earthquake.

Transmission Aqueducts

These transmission conduits are typically large size pipes (more than 20 inches in diameter) or channels (canals) that convey water from its source (reservoirs, lakes, rivers) to the treatment plant.

Transmission pipelines are commonly made of concrete, ductile iron, cast iron, or steel. These could be elevated/at grade or buried. Elevated or at grade pipes are typically made of steel (welded or riveted), and they can run in single or multiple lines.

Canals are typically lined with concrete, mainly to avoid excessive loss of water by seepage and to control erosion. In addition to concrete lining, expansion joints are usually used to account for swelling and shrinkage under varying temperature and moisture conditions. Damageability of channels has occurred in some earthquake, but is outside the scope of the scope of the methodology.

Supply Facilities- Water Treatment Plants (WTP)

Water treatment plants are generally composed of a number of physical and chemical unit processes connected in series, for the purpose of improving the water quality. A conventional WTP consists of a coagulation process, followed by a sedimentation process, and finally a filtration process. Alternately, a WTP can be regarded as a system of interconnected pipes, basins, and channels through which the water moves, and where the flow is governed by hydraulic principles. WTP are categorized as follows:

Small water treatment plants, with capacity ranging from 10 mgd to 50 mgd, are assumed to consist of a filter gallery with flocculation tanks (composed of paddles and baffles) and settling (or sedimentation) basins as main components, chemical tanks (needed in the coagulation and other destabilization processes), chlorination tanks, electrical and mechanical equipment, and elevated pipes.

Medium water treatment plants, with capacity ranging from 50 mgd to 200 mgd, are simulated by adding more redundancy to small treatment plants (i.e. twice as many flocculation, sedimentation, chemical and chlorination tanks).

Large water treatment plants, with capacity above 200 mgd, are simulated by adding even more redundancy to small treatment plants (i.e., three times as many flocculation, sedimentation, chemical and chlorination tanks/basins).

Water treatment plants are also classified based on whether the subcomponents (equipment and backup power) are anchored or not as defined in section 7.2.5.

Pumping Plants (PP)

Pumping plants are usually composed of a building, one or more pumps, electrical equipment, and in some cases, backup power systems. Pumping plants are classified as either small PP (less than 10 mgd capacity) or medium/large PP (more than 10 mgd capacity). Pumping plants are also classified with respect to whether the subcomponents (equipment and backup power) are anchored or not. As noted in Chapter 7, anchored means equipment designed with special seismic tie downs and tiebacks while unanchored means equipment with manufactures normal requirements.

Wells (WE)

Wells typically have a capacity between 1 and 5 mgd. Wells are used in many cities as a primary or supplementary source of water supply. Wells include a shaft from the surface down to the aquifer, a pump to bring the water up to the surface, equipment used to treat the water, and sometimes a building, which encloses the well and equipment.

Water Storage Tanks (ST)

Water storage tanks can be elevated steel, on ground steel (anchored/unanchored), on ground concrete (anchored/unanchored), buried concrete, or on ground wood tanks. Typical capacity of storage tanks is in the range of 0.5 mgd to 2 mgd.

Distribution Facilities and Distribution Pipes

Distribution of water can be accomplished by gravity, or by pumps in conjunction with on-line storage. Except for storage reservoirs located at a much higher altitude than the area being served, distribution of water would necessitate, at least, some pumping along the way. Typically, water is pumped at a relatively constant rate, with flow in excess of consumption being stored in elevated storage tanks. The stored water provides a reserve for fire flow and may be used for general-purpose flow should the electric power fail, or in case of pumping capacity loss.

Distribution pipelines are commonly made of concrete (prestressed or reinforced), asbestos cement, ductile iron, cast iron, steel, or plastic. The selection of material type and pipe size are based on the desired carrying capacity, availability of material, durability, and cost. Distribution pipes represent the network that delivers water to consumption areas. Distribution pipes may be further subdivided into primary lines, secondary lines, and small distribution mains. The primary or arterial mains carry flow from the pumping station to and from elevated storage tanks, and to the consumption areas, whether residential, industrial, commercial, or public. These lines are typically laid out in interlocking loops, and all smaller lines connecting to them are typically valved so that failure in smaller lines does not require shutting off the larger. Primary lines can be up to 36 inches in diameter. Secondary lines are smaller loops within the primary mains and run from one primary line to another. They serve primarily to provide a large amount of water for fire fighting without excessive pressure loss. Small distribution lines represent the mains that supply water to the user and to the fire hydrants.

In this earthquake loss estimation study, the simplified method for water system network performance evaluation applies to a distribution pipe network digitized at the primary level.

8.1.6 Definition of Damage States

Potable water systems are susceptible to earthquake damage. Facilities such as water treatment plants; wells, pumping plants and storage tanks are most vulnerable to PGA, and sometimes PGD, if located in liquefiable or landslide zones. Therefore, the damage states for these components are defined and associated with PGA and PGD. Aqueducts and pipelines, on the other hand, are vulnerable to PGV and PGD. Therefore, the damage states for these components are associated with these two ground motion parameters.

8.1.6.1 Damage State Defintions for Components Other than Pipelines

A total of five damage states for potable water system components are defined. These are none (ds_1), slight/minor (ds_2), moderate (ds_3), extensive (ds_4), and complete (ds_5).

Slight/Minor Damage **(ds_2)**

- **For water treatment plants**, ds_2 is defined by malfunction of plant for a short time (less than three days) due to loss of electric power and backup power if any, considerable damage to various equipment, light damage to sedimentation basins, light damage to chlorination tanks, or light damage to chemical tanks. Loss of water quality may occur.

- **For pumping plants**, ds_2 is defined by malfunction of plant for a short time (less than three days) due to loss of electric power and backup power if any, or slight damage to buidings.

- **For wells**, ds_2 is defined by malfunction of well pump and motor for a short time (less than three days) due to loss of electric power and backup power if any, or light damage to buidings.

- **For Storage Tanks**, ds_2 is defined by the tank suffering minor damage without loss of its contents or functionality. Minor damage to the tank roof due to water sloshing, minor cracks in concrete tanks, or localized wrinkles in steel tanks fits the description of this damage state.

Moderate Damage **(ds_3)**

- **For water treatment plants**, ds_3 is defined by malfunction of plant for about a week due to loss of electric power and backup power if any, extensive damage to various equipment, considerable damage to sedimentation basins, considerable damage to chlorination tanks with no loss of contents, or considerable damage to chemical tanks. Loss of water quality is imminent.

- **For pumping plants**, ds_3 is defined by the loss of electric power for about a week, considerable damage to mechanical and electrical equipment, or moderate damage to buildings.

- **For wells**, ds_3 is defined by malfunction of well pump and motor for about a week due to loss of electric power and backup power if any, considerable damage to mechanical and electrical equipment, or moderate damage to buildings.

- **For Storage Tanks**, ds_3 is defined by the tank being considerably damaged, but only minor loss of content. Elephant foot buckling for steel tanks without loss of content, or moderate cracking of concrete tanks with minor loss of content fits the description of this damage state.

<u>Extensive Damage</u> (ds_4)

- **<u>For water treatment plants</u>**, ds_4 is defined by the pipes connecting the different basins and chemical units being extensively damaged. This type of damage will likely result in the shutdown of the plant.

- **<u>For pumping plants</u>**, ds_4 is defined by the building being extensively damaged, or the pumps being badly damaged beyond repair.

- **<u>For wells</u>**, ds_4 is defined by the building being extensively damaged or the well pump and vertical shaft being badly distorted and nonfunctional.

- **<u>For Storage Tanks</u>**, ds_4 is defined by the tank being severely damaged and going out of service. Elephant foot buckling for steel tanks with loss of content, stretching of bars for wood tanks, or shearing of wall for concrete tanks fits the description of this damage state.

<u>Complete Damage</u> (ds_5)

- **<u>For water treatment plants</u>**, ds_5 is defined by the complete failure of all pipings, or extensive damage to the filter gallery.

- **<u>For pumping plants</u>**, ds_5 is defined by the building collapsing.

- **<u>For wells</u>**, ds_5 is defined by the building collapsing.

- **<u>For Storage Tanks</u>**, ds_5 is defined by the tank collapsing and losing all of its content.

8.1.6.2 Defintion of Damage States for Pipelines

For pipelines, two damage states are considered. These are leaks and breaks. Generally, when a pipe is damaged due to ground failure (PGD), the type of damage is likely to be a break, while when a pipe is damaged due to seismic wave propagation (PGV), the type of damage is likely to be joint pull-out or crushing at the bell. In the loss methodology, it is assumed that damage due to seismic waves will consist of 80% leaks and 20% breaks, while damage due to ground failure will consist of 20% leaks and 80% breaks. The user can override these default percentages.

8.1.7 Component Restoration Curves

Restoration functions for potable water system components, namely, water treatment plants, wells, pumping plants, and storage tanks are based on SF-30a, SF-30b and SF-30d of ATC-13 consistent with damage states defined in the previous section. That is, restoration functions for ds_2, ds_3, ds_4, and ds_5 defined herein are assumed to correspond to ds_2, ds_3, ds_4, and ds_5 of ATC-13. The parameters of these restoration curves are given in Tables 8.1.a and 8.1.b, and 8.1.c.

Table 8.1.a: Continuous Restoration Functions for Potable Water Systems (After ATC-13, 1985)

Restoration Functions (All Normal Distributions)			
Classification	**Damage State**	**Mean (Days)**	**σ (days)**
Water Treatment Plants	slight/minor	0.9	0.3
	moderate	1.9	1.2
	extensive	32.0	31.0
	complete	95.0	65.0
Pumping Plants	slight/minor	0.9	0.3
	moderate	3.1	2.7
	extensive	13.5	10.0
	complete	35.0	18.0
Wells	slight/minor	0.8	0.2
	moderate	1.5	1.2
	extensive	10.5	7.5
	complete	26.0	14.0
Water Storage Tanks	slight/minor	1.2	0.4
	moderate	3.1	2.7
	extensive	93.0	85.0
	complete	155.0	120.0

Table 8.1.a gives means and standard deviations for each restoration curve (i.e., smooth continuous curve), while Table 8.1.b gives approximate discrete functions for the restoration curves developed. These restoration functions are also shown in Figures 8.1 through 8.4.

Table 8.1.b: Discretized Restoration Functions for Potable Water System Components

Discretized Restoration Functions						
Classification	**Damage State**	**1 day**	**3 days**	**7 days**	**30 days**	**90 days**
Water Treatment Plants	slight/minor	65	100	100	100	100
	moderate	23	82	100	100	100
	extensive	16	18	21	48	97
	complete	7	8	9	16	47
Pumping Plants	slight/minor	65	100	100	100	100
	moderate	22	50	93	100	100
	extensive	10	15	25	95	100
	complete	3	4	6	40	100

Table 8.1.b: Discretized Restoration Functions for Potable Water System Components (continued)

Discretized Restoration Functions						
Classification	**Damage State**	**1 day**	**3 days**	**7 days**	**30 days**	**90 days**
Wells	slight/minor	85	100	100	100	100
	moderate	34	90	100	100	100
	extensive	11	16	33	100	100
	complete	4	6	9	62	100
Water Storage Tanks	slight/minor	30	100	100	100	100
	moderate	20	49	93	100	100
	extensive	13	15	16	23	49
	complete	10	11	12	15	30

The restoration functions for pipelines are expressed in terms of number of days needed to fix the leaks and breaks. These restoration functions are given in Table 8.1.c

Table 8.1.c: Restoration Functions for Potable Water Pipelines

Class	Diameter from: [in]	Diameter to: [in]	# Fixed Breaks per Day per Worker	# Fixed Leaks per Day per Worker	# Available Workers	Priority
a	60	300	0.33	0.66	User-specified	1 (Highest)
b	36	60	0.33	0.66	User-specified	2
c	20	36	0.33	0.66	User-specified	3
d	12	20	0.50	1.0	User-specified	4
e	8	12	0.50	1.0	User-specified	5 (Lowest)
u	Unknown diameter	or for Default Data Analysis	0.50	1.0	User-specified	6 (lowest)

Where the total number of available workers can be specified by the user. It should be noted that the values in Table 8.1.c are based on the following 4 assumptions:

(1) "Pipes that are less than 20" in diameter are defined as small, while pipes with diameter greater than 20" are defined as large."
(2) For both small and large pipes a 16 hour day shift is assumed.
(3) For small pipes, a 4-person crew needs 4 hours to fix a leak, while the same 4-person crew needs 8 hours to fix a break. (Mathematically, this is equivalent to saying it takes 16 people to fix a leak in one hour and it takes 32 people to fix a break in one hour).
(4) For large pipes, a 4-person crew needs 6 hours to fix a leak, while the same 4-person crew needs 12 hours to fix a break. (Mathematically, this is equivalent to say it takes 24 people to fix a leak in one hour and 48 people to fix a break in one hour).

With this algorithm for potable water pipelines, the total number of days needed to finish repairs is calculated as:

Days needed to finish all repairs = (1/available work) * [(# small pipe leaks/1.0) + (# small pipe breaks/0.5) +(# large pipe leaks/0.66) + (# large pipe breaks/0.33)]

The percentage of repairs finished at Day1, Day3, Day7, Day30, and Day90 are then computed using linear interpolation.

8.1.8 Development of Damage Functions

In this subsection, damage functions for the various components of a potable water system are presented. In cases where the components are made of subcomponents (i.e., water treatment plants, pumping plants, and wells), fragility curves for these components are based on the probabilistic combination of subcomponent damage functions using Boolean expressions to describe the relationship of subcomponents to the components. It should be mentioned that the Boolean logic is implicitly presented within the definition of a particular damage state. For example, slight/minor damage for a water treatment plant was defined by malfunction for a short time due to loss of electric power AND backup power (if any), considerable damage to various equipment, light damage to sedimentation basins, light damage to chlorination tanks, OR light damage to chemical tanks. Therefore, the fault tree for slight/minor damage has FIVE primary OR branches: electric power, equipment, sedimentation basins, chlorination tanks, and chemical tanks, and TWO secondary AND branches under electric power: commercial power and backup power. The Boolean approach involves evaluation of the probability of each component reaching or exceeding different damage states, as defined by the damage level of its subcomponents. These evaluations produce component probabilities at various levels of ground motion. In general, the Boolean combinations do not produce a lognormal distribution, so a lognormal curve that best fits this probability distribution is determined numerically. It should be mentioned that damage functions due to ground failure (i.e., PGD) for all potable water systems components except pipelines (i.e., water treatment plants, pumping plants, wells, and storage tanks) are assumed to be similar to those described for buildings, unless specified otherwise. These are:

- For lateral spreading, a lognormal damage function with a median of 60 inches and a dispersion of 1.2 is assumed for the damage state of "at least extensive". 20% of this damage is assumed to be complete. For a PGD of 10 inches due to lateral spreading, there is a 7% probability of "at least extensive" damage.

For vertical settlement, a lognormal curve with a median of 10 inches and a dispersion of 1.2 is assumed for the damage state of "at least extensive". 20% of this damage is assumed to be complete. For a PGD of 10" due to vertical settlement, there is a 50% chance of "at least extensive" damage.

- For fault movement or landslide, a lognormal curve with a median of 10 inches and a dispersion of 0.5 is assumed for "complete" damage state. That is, for 10 inches of PGD due to fault movement or landslide, there is a 50% chance of "complete" damage.

An example of how to combine a PGD algorithm with a PGA algorithm for lifeline components was presented in section 7.2.8 of Chapter 7.

<u>Damage Functions for Water Treatment Plants (due to Ground Shaking)</u>

PGA related damage functions for water treatment plants are developed with respect to their classification. A total of 24 damage functions are presented. Half of these damage functions correspond to water treatment plants with anchored subcomponents, while the other half correspond to water treatment plants with unanchored subcomponents (see section 7.2.5 for the definition of anchored and unanchored subcomponents). Medians and dispersions of these damage functions are given in Tables 8.3 through 8.5.

Medians and dispersions of damage functions for the water treatment plant subcomponents are summarized in Tables A.8.6 and A.8.7 of Appendix 8A. The medians for elevated pipe damage functions in these tables are based on ATC-13 data (FC-32) for "at grade pipe" using the following MMI to PGA conversion (after G&E, 1994), along with a best-fit lognormal curve.

Table 8.2: MMI to PGA Conversion (after G&E, 1994)

MMI	VI	VII	VIII	IX	X	XI	XII
PGA	0.12	0.21	0.36	0.53	0.71	0.86	1.15

Graphical representations of water treatment plant damage functions are also provided. Figures 8.5 through 8.10 are fragility curves for the different classes of water treatment plants.

Table 8.3: Damage Algorithms for Small Water Treatment Plants

Peak Ground Acceleration			
Classification	**Damage State**	**Median (g)**	**β**
Plants with anchored subcomponents (PWT1)	slight/minor moderate extensive complete	0.25 0.38 0.53 0.83	0.50 0.50 0.60 0.60
Plants with unanchored subcomponents (PWT2)	slight/minor moderate extensive complete	0.16 0.27 0.53 0.83	0.40 0.40 0.60 0.60

Table 8.4: Damage Algorithms for Medium Water Treatment Plants

Peak Ground Acceleration			
Classification	**Damage State**	**Median (g)**	**β**
Plants with anchored subcomponents (PWT3)	slight/minor moderate extensive complete	0.37 0.52 0.73 1.28	0.40 0.40 0.50 0.50
Plants with unanchored subcomponents (PWT4)	slight/minor moderate extensive complete	0.20 0.35 0.75 1.28	0.40 0.40 0.50 0.50

Table 8.5: Damage Algorithms for Large Water Treatment Plants

Peak Ground Acceleration			
Classification	**Damage State**	**Median (g)**	**β**
Plants with anchored subcomponents (PWT5)	slight/minor moderate extensive complete	0.44 0.58 0.87 1.57	0.40 0.40 0.45 0.45
Plants with unanchored subcomponents (PWT6)	slight/minor moderate extensive complete	0.22 0.35 0.87 1.57	0.40 0.40 0.45 0.45

Damage Functions for Pumping Plants (due to Ground Shaking)

PGA related damage functions for pumping plants are developed with respect to their classification. A total of 16 damage functions are presented. Half of these damage functions correspond to pumping plants with anchored subcomponents, while the other half correspond to pumping plants with unanchored subcomponents. Medians and dispersions of these damage functions are given in Tables 8.6 and 8.7. Graphical representations of damage functions for the different classes of pumping plants are presented in Figures 8.11 through 8.14. Note that medians and dispersions of damage functions for pumping plants' subcomponents are summarized in Appendix 8A.

Table 8.6: Damage Algorithms for Small Pumping Plants

Peak Ground Acceleration			
Classification	**Damage State**	**Median (g)**	**β**
Plants with anchored subcomponents (PPP1)	slight/minor	0.15	0.70
	moderate	0.36	0.65
	extensive	0.66	0.65
	complete	1.50	0.80
Plants with unanchored subcomponents (PPP2)	slight/minor	0.13	0.60
	moderate	0.28	0.50
	extensive	0.66	0.65
	complete	1.50	0.80

Table 8.7: Damage Algorithms for Medium/Large Pumping Plants

Peak Ground Acceleration			
Classification	**Damage State**	**Median (g)**	**β**
Plants with anchored subcomponents (PPP3)	slight/minor	0.15	0.75
	moderate	0.36	0.65
	extensive	0.77	0.65
	complete	1.50	0.80
Plants with unanchored subcomponents (PPP4)	slight/minor	0.13	0.60
	moderate	0.28	0.50
	extensive	0.77	0.65
	complete	1.50	0.80

Damage Functions for Wells (due to Ground Shaking)

A total of four PGA-related damage functions are presented. In developing these damage functions, it is assumed that equipment in wells is anchored. Medians and dispersions of these damage functions are given in Table 8.8. Graphical representations of well damage functions are also shown in Figure 8.15. Note that medians and dispersions of damage functions for well subcomponents are summarized in Appendix 8A.

Table 8.8: Damage Algorithms for Wells

Peak Ground Acceleration			
Classification	**Damage State**	**Median (g)**	**β**
Wells (PWE1)	slight/minor	0.15	0.75
	moderate	0.36	0.65
	extensive	0.72	0.65
	complete	1.50	0.80

Damage Functions for Water Storage tanks

A total of 24 PGA related damage functions are developed. These correspond to on-ground concrete (anchored and unanchored), on ground steel (anchored and unanchored), elevated steel, and on-ground wood tanks. For tanks, anchored and unanchored refers to positive connection, or a lack thereof, between the tank wall and the supporting concrete ring wall. The PGD algorithm associated with these water storage tanks is described at the beginning of section 8.1.8. For buried storage tanks a separate PGD algorithm is presented. Medians and dispersions of the PGA related damage functions are given in Table 8.9. Graphical representations of water storage tank damage functions are also provided. Figures 8.16 through 8.21 are fragility curves for the different classes of water storage tanks.

Table 8.9: Damage Algorithms for Water Storage Tanks

Peak Ground Acceleration			
Classification	**Damage State**	**Median (g)**	**β**
On-Ground Anchored Concrete Tank (PST1)	slight/minor	0.25	0.55
	moderate	0.52	0.70
	extensive	0.95	0.60
	complete	1.64	0.70
On-Ground Unanchored Concrete Tank (PST2)	slight/minor	0.18	0.60
	moderate	0.42	0.70
	extensive	0.70	0.55
	complete	1.04	0.60
On-Ground Anchored Steel Tank (PST3)	slight/minor	0.30	0.60
	moderate	0.70	0.60
	extensive	1.25	0.65
	complete	1.60	0.60
On-Ground Unanchored Steel Tank (PST4)	slight/minor	0.15	0.70
	moderate	0.35	0.75
	extensive	0.68	0.75
	complete	0.95	0.70
Above-Ground Steel Tank (PST5)	slight/minor	0.18	0.50
	moderate	0.55	0.50
	extensive	1.15	0.60
	complete	1.50	0.60
On-Ground Wood Tank (PST6)	slight/minor	0.15	0.60
	moderate	0.40	0.60
	extensive	0.70	0.70
	complete	0.90	0.70
Permanent Ground Deformation			
Classification	**Damage State**	**Median (in)**	**β**
Buried Concrete Tank (PST7)	slight/minor	2	0.50
	moderate	4	0.50
	extensive	8	0.50
	complete	12	0.50

Damage Functions for Buried Pipelines

Two damage algorithms are used for buried pipelines. The first algorithm is associated with peak ground velocity (PGV) while the second algorithm is associated with permanent ground deformation (PGD). Note that in both of these algorithms the diameter of pipe is not considered to be a factor.

The PGV algorithm is based on the empirical data presented in a work done by O'Rourke and Ayala (1993). The data correspond to actual pipeline damage observed in four US and two Mexican earthquakes. This data is plotted in Figure 8.22.a. The following relation represents a good fit for this empircal data:

$$\text{Repair Rate [Repairs/Km]} \cong 0.0001 \text{ x } (\text{PGV})^{(2.25)}$$

With PGV expressed in cm/sec. Note that the data plotted in Figure 8.22.a correspond to asbestos cement, concrete and cast iron pipes; therefore, the above (RR to PGV) relation is assumed to apply for brittle pipelines. For ductile pipelines (steel, ductile iron and PVC), the above relation is multiplied by 0.3. That is, ductile pipelines have 30% of the vulnerability of brittle pipelines. Note that welded steel pipes with arc-welded joints are classified as ductile, and that welded steel pipes with gas-welded joints are classified as brittle. It is conceivable that the only other information available to the user regarding steel pipes is the year of installation. In this case, the user should classify pre-1935 steel pipes as brittle pipes.

The damage algorithm for buried pipelines due to ground failure is based on work conducted by Honegger and Eguchi (1992) for the San Diego County Water Authority (SDCWA). Figure 8.22.b shows the base fragility curve for cast iron pipes. The best-fit function to this curve is given by:

$$\text{Repair Rate [Repairs/Km]} \cong \text{Prob [liq] x PGD}^{(0.56)}$$

With PGD expressed in inches. This RR to PGD relation is assumed to apply for brittle pipelines. For ductile pipelines, the same multiplier as the PGV algorithm is assumed (i.e., 0.3).

To summarize, the pipeline damage algorithms that are used in the current loss estimation methodology are presented in Table 8.10

Table 8.10: Damage Algorithms for Water Pipelines

	PGV Algorithm		PGD Algorithm	
	R. R. ≅ 0.0001 x PGV$^{(2.25)}$		R. R. ≅ Prob[liq]xPGD$^{(0.56)}$	
Pipe Type	Multiplier	Example of Pipe	Multiplier	Example of Pipe
Brittle Pipes (PWP1)	1	CI, AC, RCC	1	CI, AC, RCC
Ductile Pipes (PWP2)	0.3	DI, S, PVC	0.3	DI, S, PVC

8.1.9 System Performance

In the previous section, damage algorithms for the various components of a water system were presented. For the level 2 enhanced analysis (i.e., assuming the commercial data was readily available and processed as described in the "Potable Water System Analysis Model" manual), this information is combined and a system network analysis is performed.

This section, however, outlines the simplified methodology that is used in the level 1 and level 2 analyses and which allows for a quick evaluation of the system performance in the aftermath of an earthquake.

This approach is based on system performance studies done for water networks in Oakland, Tokyo, and San Francisco. In the Tokyo study (Isoyama and Katayama, 1982), water system network performance evaluations following an earthquake were simulated for two different supply strategies: (1) supply priority to nodes with larger demands, and (2) supply priority to nodes with lowest demands. The "best" and "worst" node performances are approximately reproduced in a different format in Figure 8.23. The probability of pipeline failure, which was assumed to follow a Poisson process in the original paper, was substituded with the average break rate which was backcalculated based on a pipeline link length of about 5 kilometers (i.e., in the trunk network of the water supply system of Tokyo, the average link length is about 5 kilometers). Note that in this figure, serviceability index is considered as a measure of the reduced flow.

Recently, researchers at Cornell University (Markov, Grigoriu and O'Rourke, 1994) evaluated the San Francisco auxiliary (fire fighting) water supply system (AWSS). Some of their results are reproduced and shown also in Figure 8.23.

G&E (1994) also did a similar study for the EBMUD (East Bay Municipal District) water supply system. Their results are shown as well in Figure 8.23.

Based on these results, the damage algorithm proposed in this earthquake loss estimation for the simplified system performance evaluation is defined by a "conjugate" lognormal function (i.e., 1 - lognormal function). This damage function has a median of 0.1 repairs/km and a beta of 0.85, and it is shown in Figure 8.23. Hence, given knowledge of the pipe classification and length, one can estimate the system performance. That is, damage algorithms provided in the previous section give repair rates and therefore the expected total number of repairs (i.e., by multiplying the expected repair rate for each pipe type in the network by its length and summing up over all pipes in the network). The average repair rate is then computed as the ratio of the expected total number of repairs to the total length of pipes in the network.

Example
Assume we have a pipeline network of total length equal to 500 kilometers, and that this network is mainly composed of 16" diameter brittle pipes with each segment being 20 feet in length. Assume also that this pipeline is subject to both ground shaking and ground failure as detailed in Table 8.11. Note that the repair rates (R.R.) in this table are computed based on the equations provided in section 8.1.8.

Table 8.11: Example of System Performance Evaluation

PGV (cm/sec)	R.R. (Re/km)	Length (km)	# Repairs	PGD (inches)	Probab. of Lique	R.R. (Re/km)	Length (km)	# Repairs
35	0.2980	50	~ 15	18	1.0	5.0461	1	~ 5
30	0.2106	50	~ 11	12	1.0	4.0211	1	~ 4
25	0.1398	50	~ 7	6	0.80	2.7275	5	~ 11
20	0.0846	50	~ 4	2	0.65	1.4743	53	~ 51
15	0.0443	100	~ 4	1	0.60	1	20	12
10	0.0178	100	~ 2	0.5	0.40	0.6783	20	~ 6
5	0.0038	100	0	0	0.10	0	400	0
	Total	500	43			Total	500	89

Therefore, due to PGV, the estimated number of leaks is 80% x 43 = 34, and the estimated number of breaks is 9, while due to PGD, the estimated number of leaks is 20% x 89 = 18 and the estimated number of breaks is 71.

When we apply the "conjugate" lognormal damage function, which has a median of 0.1 repairs/km and a beta of 0.85, first we compute conservatively the average break rate as:

- Average break rate = (9 + 71) / 500 = 0.16 repairs/km

Hence, the serviceability index <u>right after the earthquake</u> is:

- Serviceability Index = 1 - Lognormal(0.16, 0.1, 0.85) = 0.29 or 29 %

8.1.10 Guidance for Loss Estimation Using Advanced Data and Models Analysis

For this type of analysis, the expert can use the methodology developed with the flexibility to (1) include a more refined inventory of the water system pertaining to the area of study, (2) include component-specific and system-specific fragility data, and (3) utilize a commercial model to estimate overall system functionality. Default damage algorithms can be modified or replaced to incorporate improved information about key components of a water system. Similarly, better restoration curves can be developed, given knowledge of available resources and a more accurate layout of the water network within the local topographic and geological conditions.

8.1.11 References

(1) ATC-13, "Earthquake Damage Evaluation Data for California", Applied Technology Council, Redwood City, CA, 1985.

(2) G&E Engineering Systems, Inc. (G&E), "NIBS Earthquake Loss Estimation Methods, Technical Manual, (Water Systems)", May 1994.

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(7) K/J/C and Dames & Moore, "Earthquake Loss Estimation for the City of Everett, Washington Lifelines", May 1991.

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(12) Isoyama R. and Katayama T., "Reliability Evaluation of Water Supply Systems During Earthquakes", February 1982.

(13) Khater M and Waisman F., "Potable Water System Analysis Model (POWSAM)", September 1999. NIBS technical report.

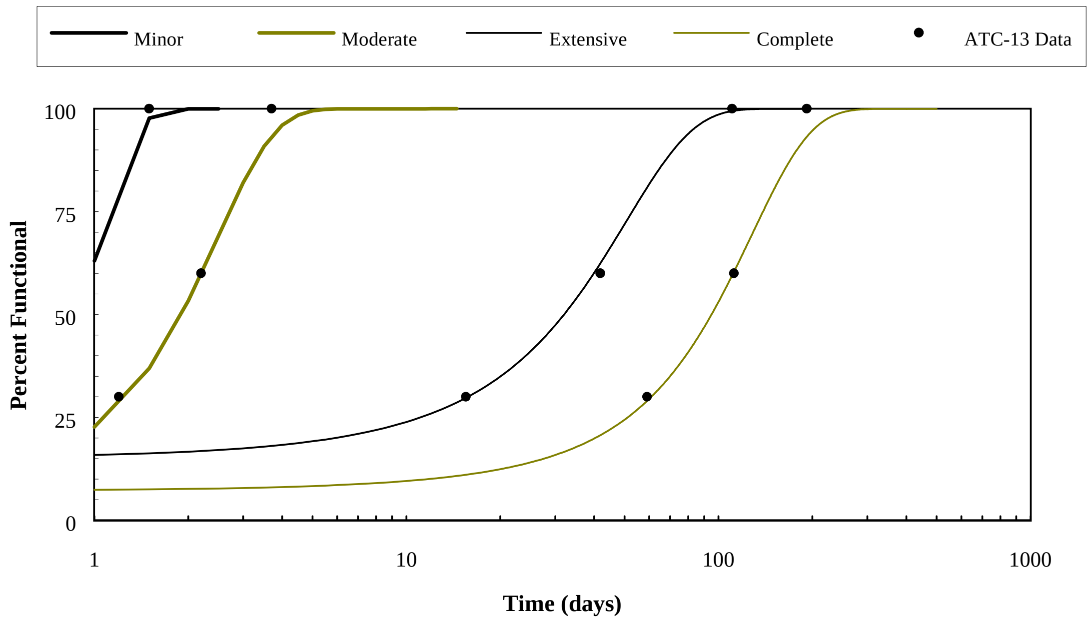


Figure 8.1: Restoration Curves for Water Treatment Plants (after ATC-13, 1985).

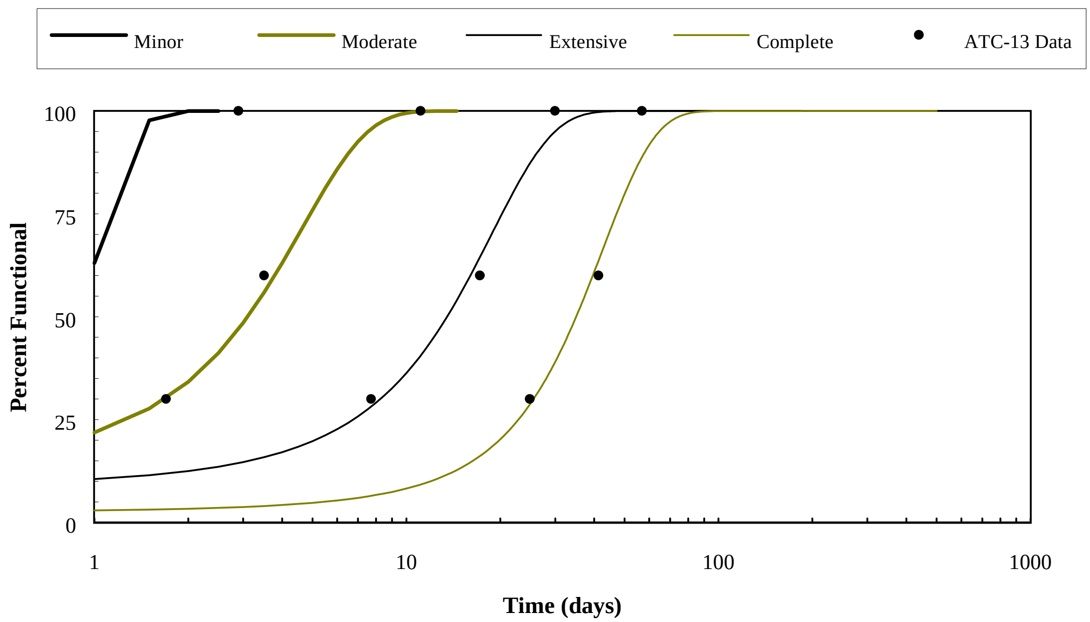


Figure 8.2: Restoration Curves for Pumping Plants (after ATC-13, 1985).

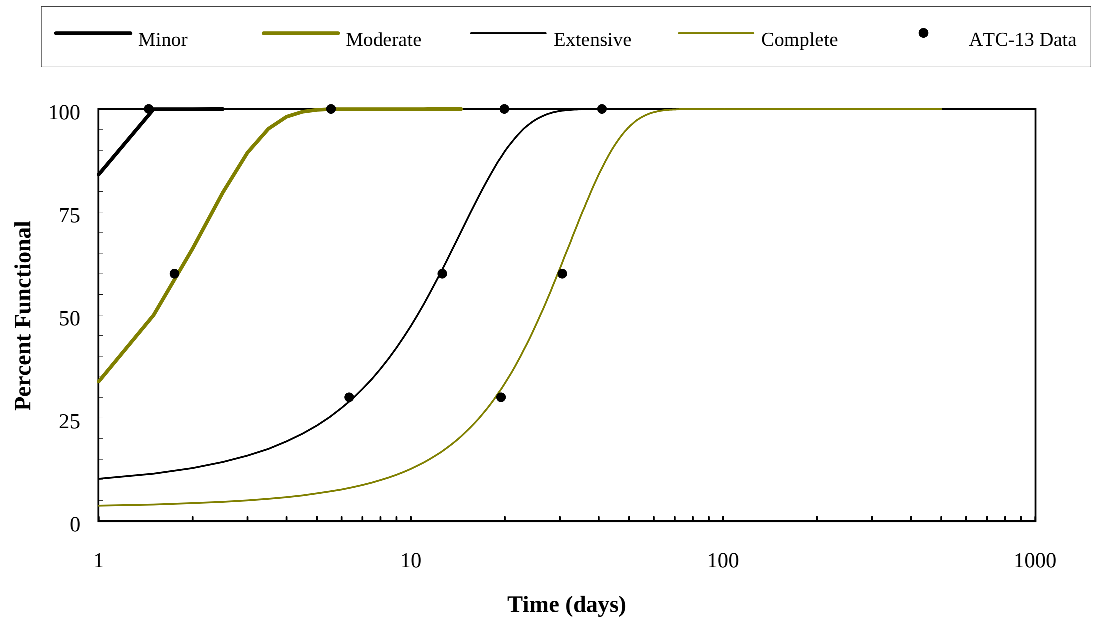


Figure 8.3: Restoration Curves for Wells (after ATC-13, 1985).

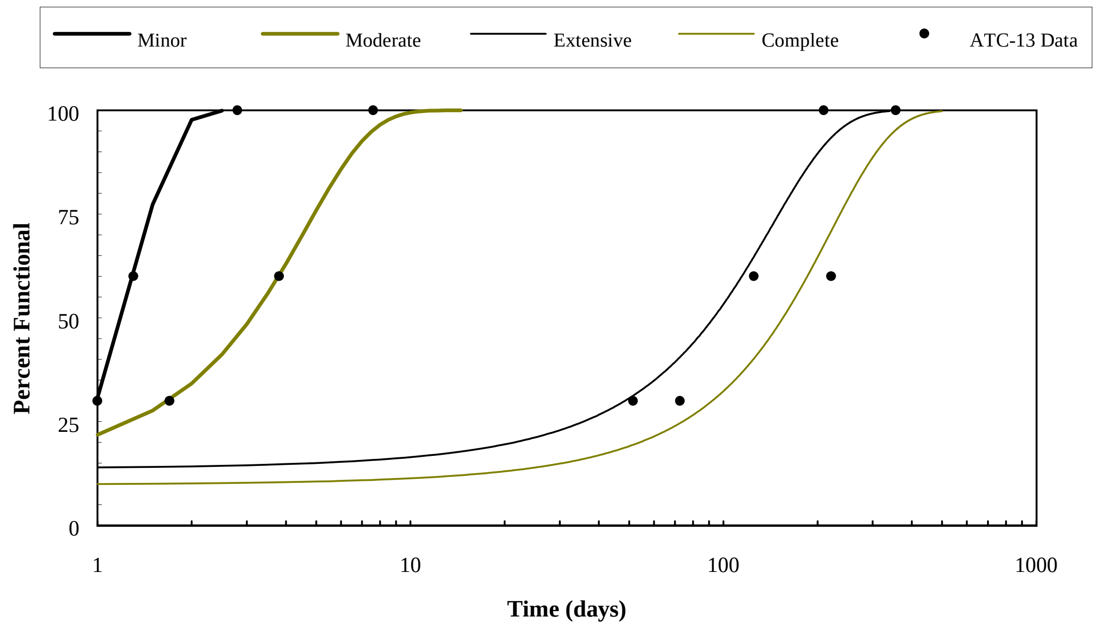


Figure 8.4: Restoration Curves for Water Storage Tanks (after ATC-13, 1985).

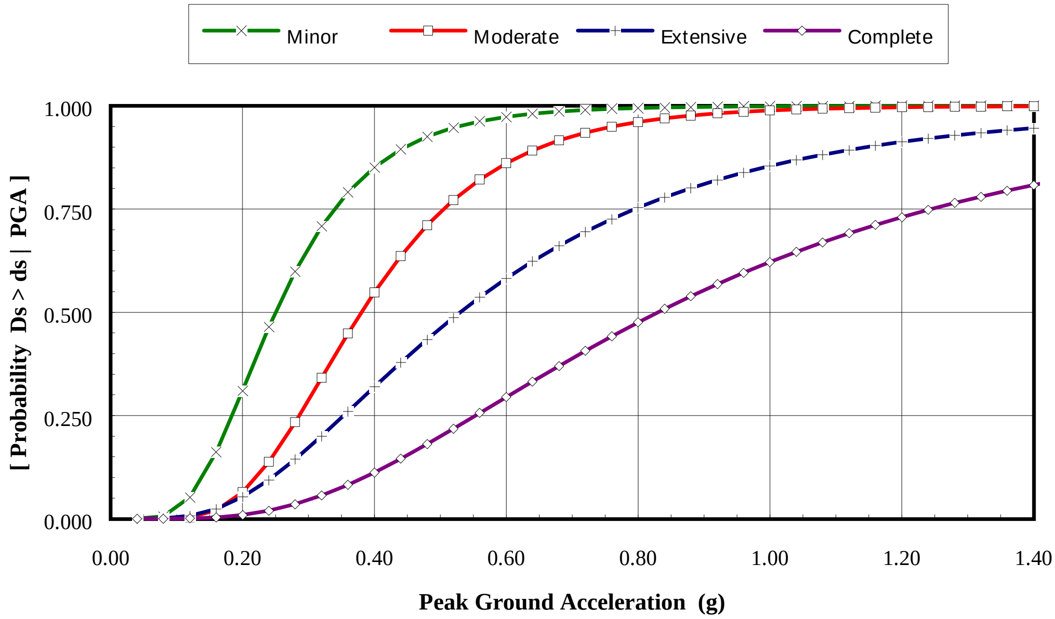


Figure 8.5: Fragility Curves for Small Water Treatment Plants with Anchored Components.

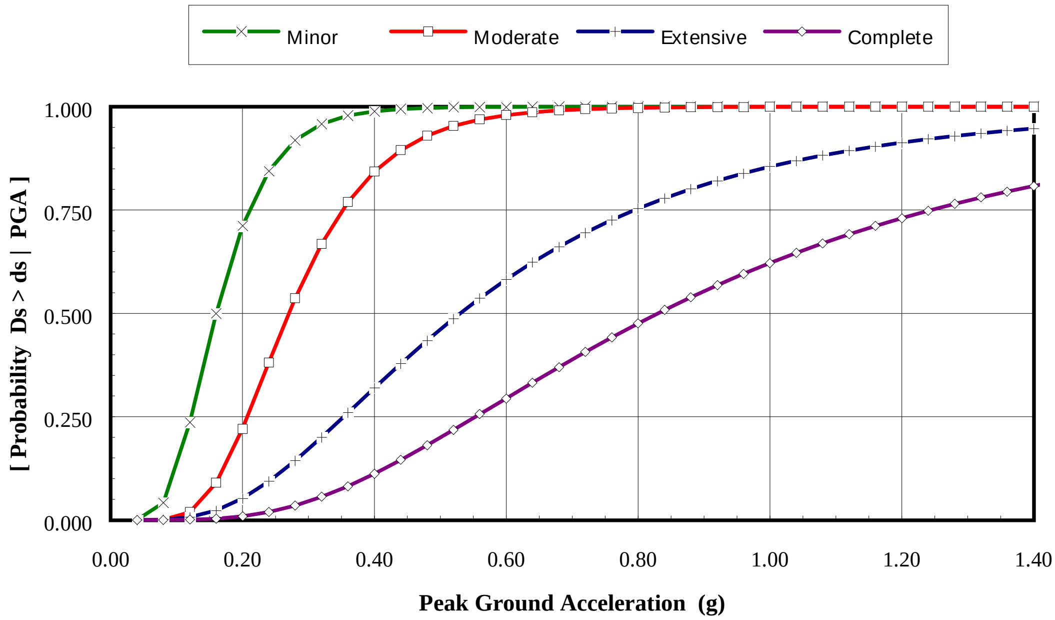


Figure 8.6: Fragility Curves for Small Water Treatment Plants with Unanchored Components.

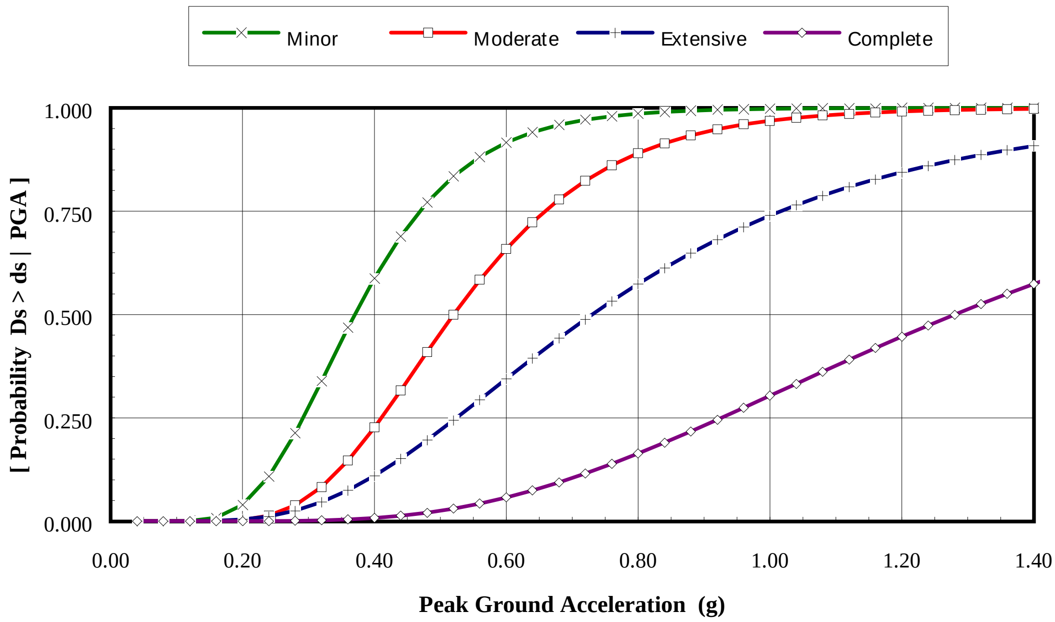


Figure 8.7: Fragility Curves for Medium Water Treatment Plants with Anchored Components.

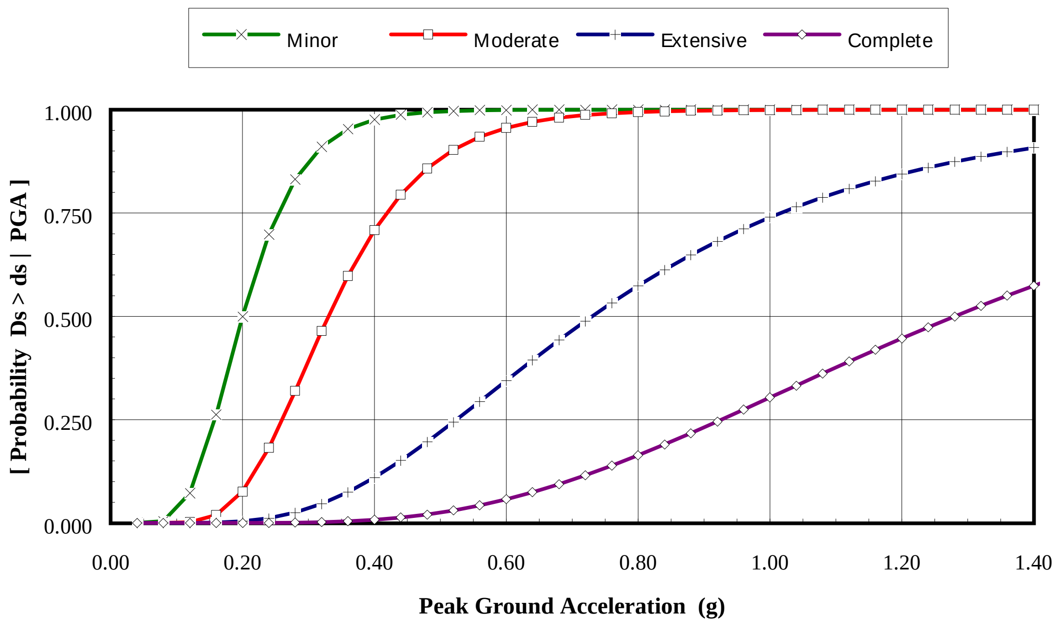


Figure 8.8: Fragility Curves for Medium Water Treatment Plants with Unanchored Components.

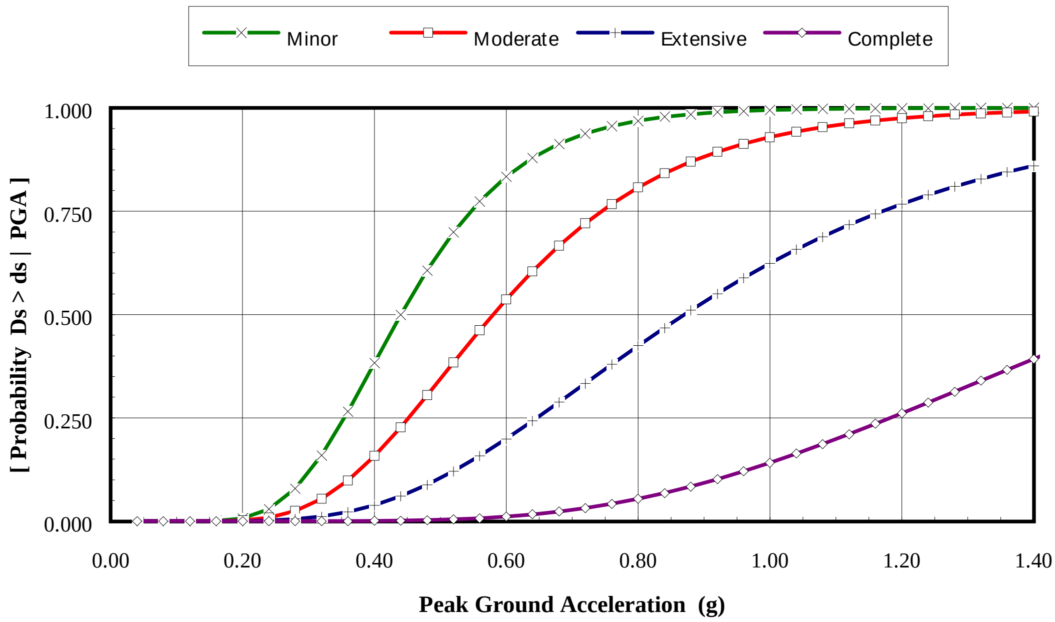


Figure 8.9: Fragility Curves for Large Water Treatment Plants with Anchored Components.

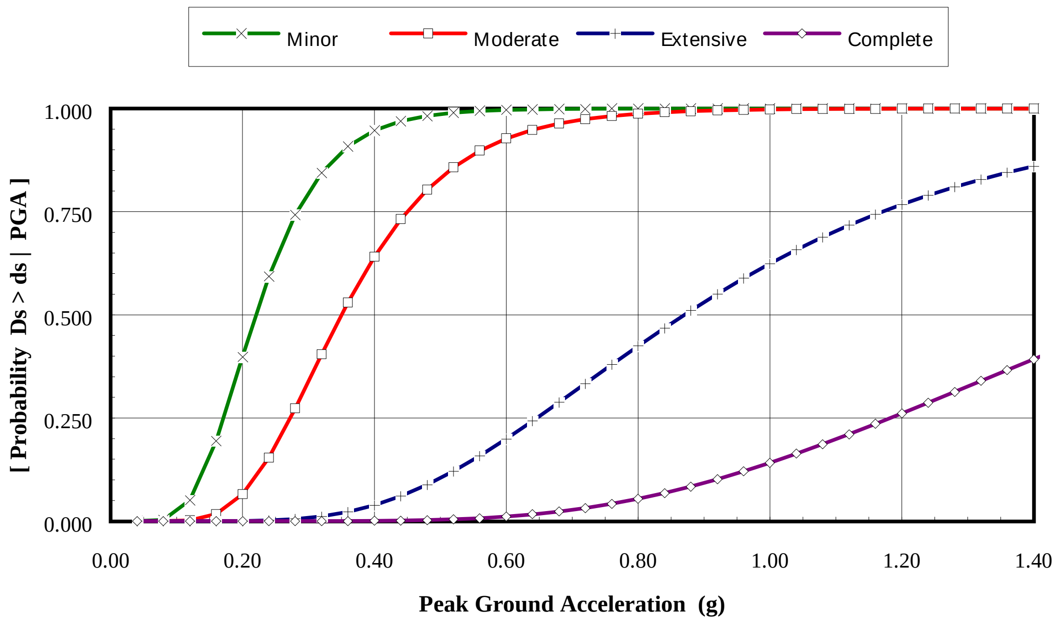


Figure 8.10: Fragility Curves for Large Water Treatment Plants with Unanchored Components.

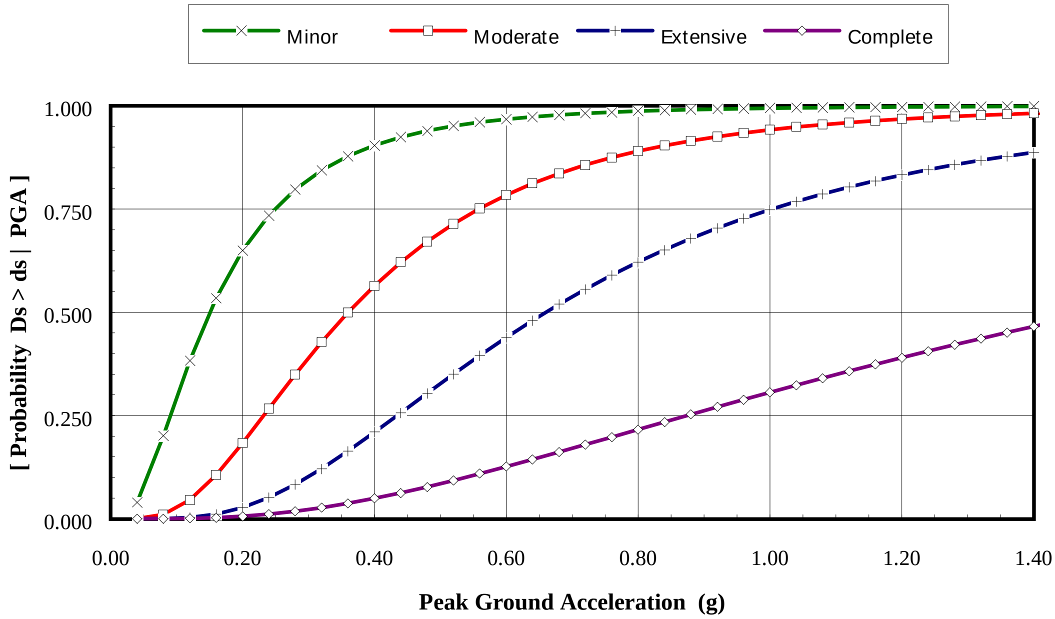


Figure 8.11: Fragility Curves for Small Pumping Plants with Anchored Components.

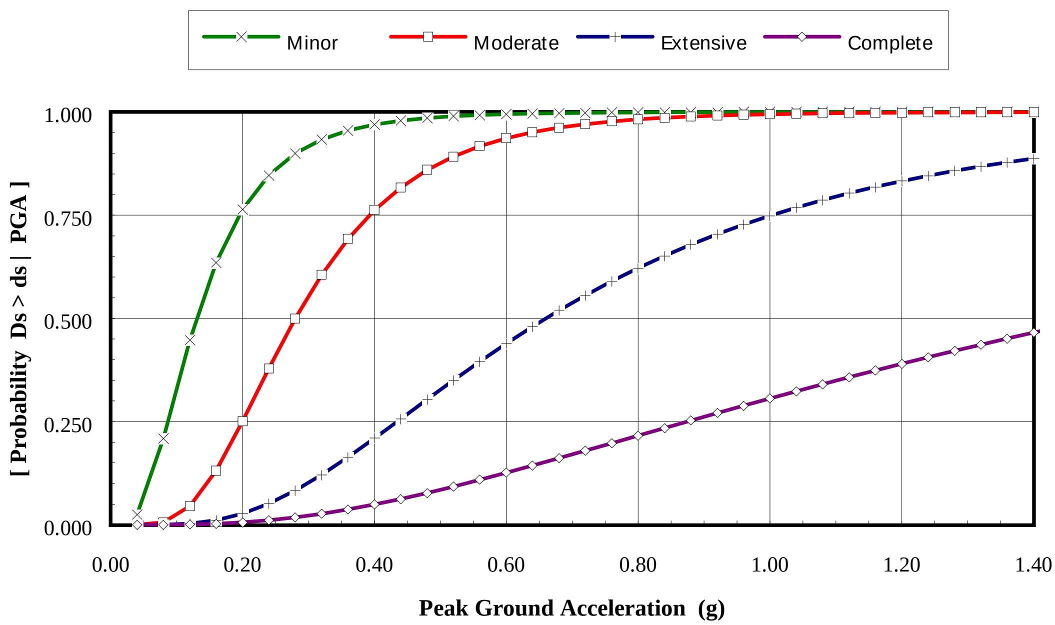


Figure 8.12: Fragility Curves for Small Pumping Plants with Unanchored Components.

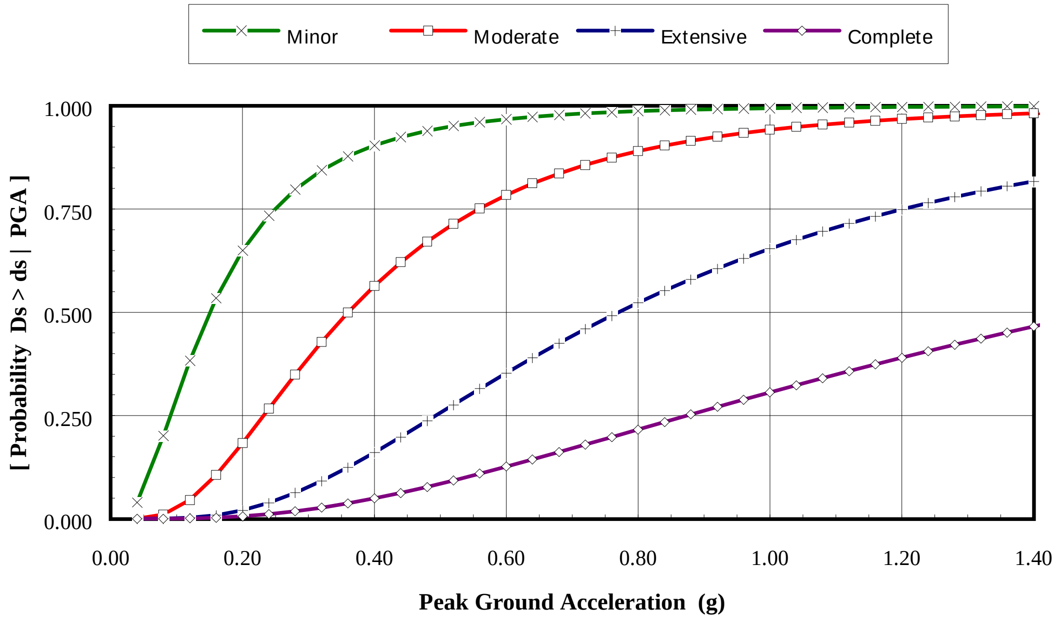


Figure 8.13: Fragility Curves for Medium/Large Pumping Plants with Anchored Components.

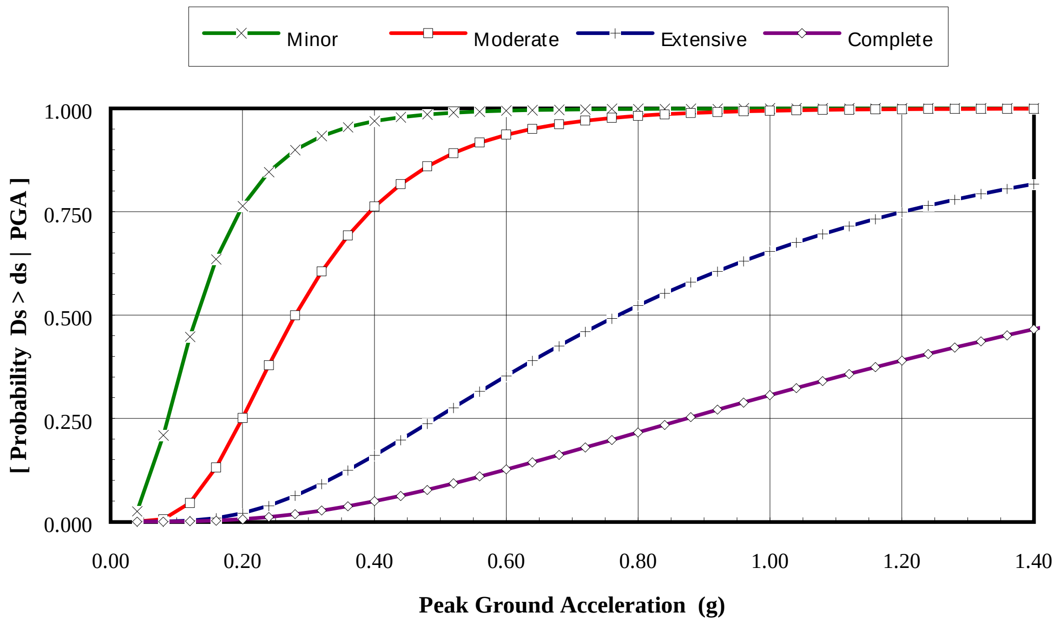


Figure 8.14: Fragility Curves for Medium/Large Pumping Plants with Anchored Components.

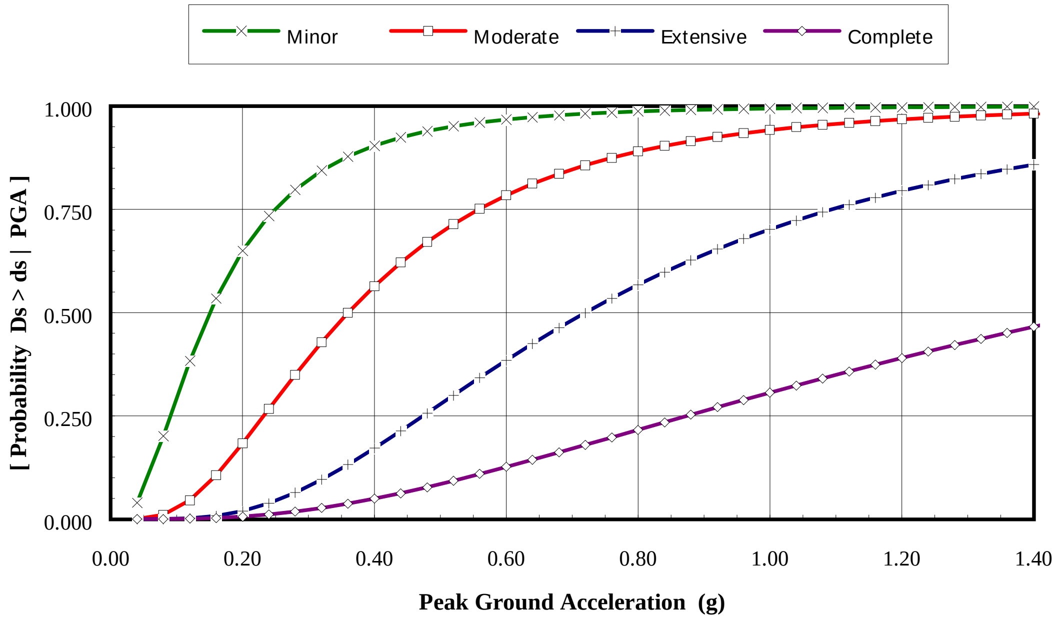


Figure 8.15: Fragility Curves for Wells

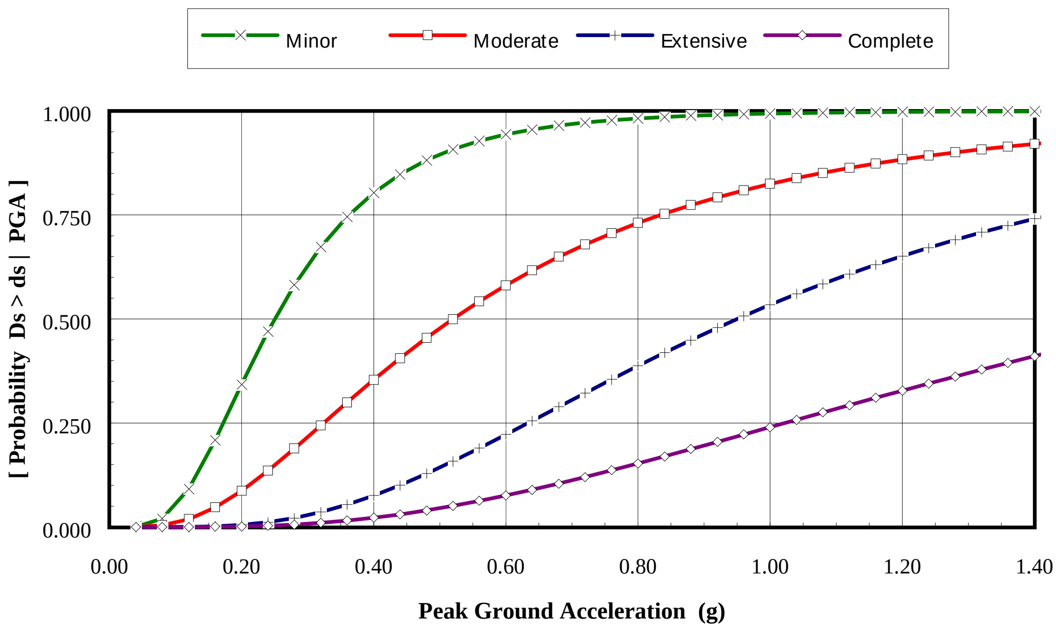


Figure 8.16: Fragility Curves for Anchored On Ground Concrete Tank.

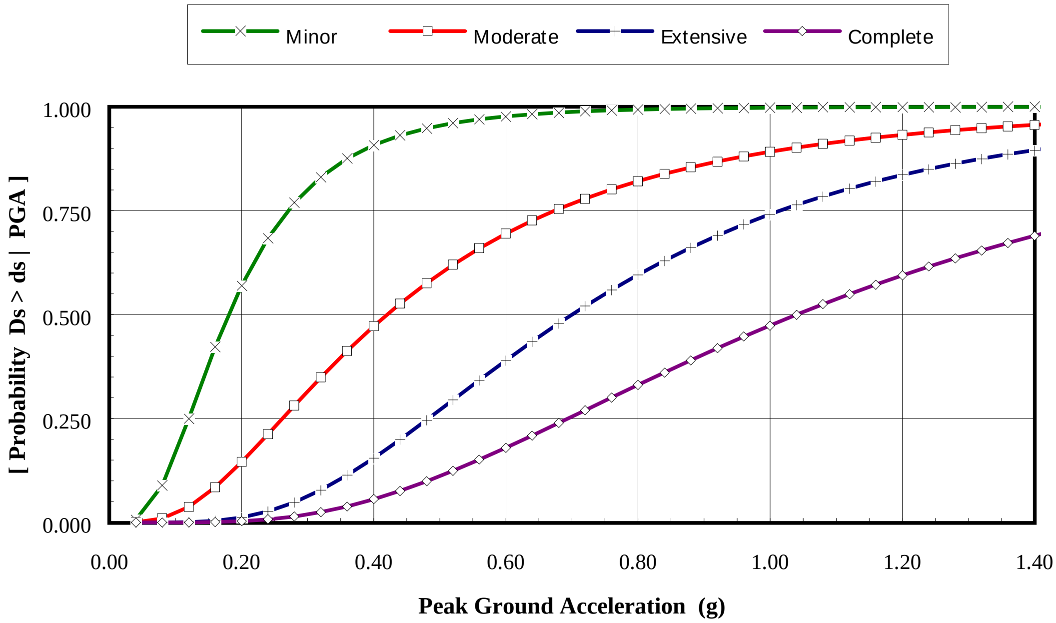


Figure 8.17: Fragility Curves for Unanchored On Ground Concrete Tank.

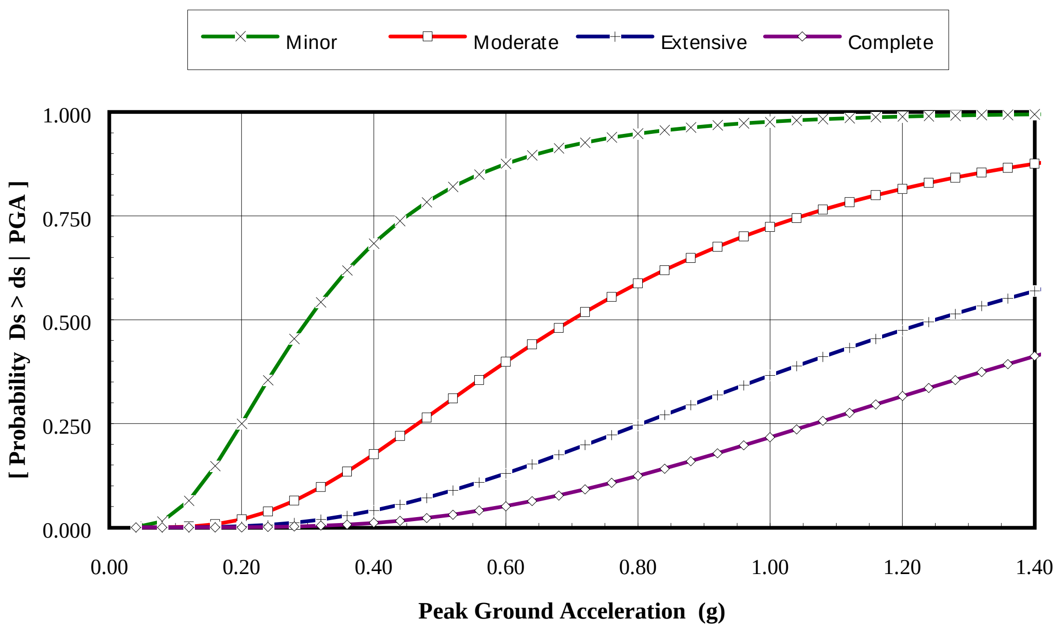


Figure 8.18: Fragility Curves for Anchored On Ground Steel Tank.

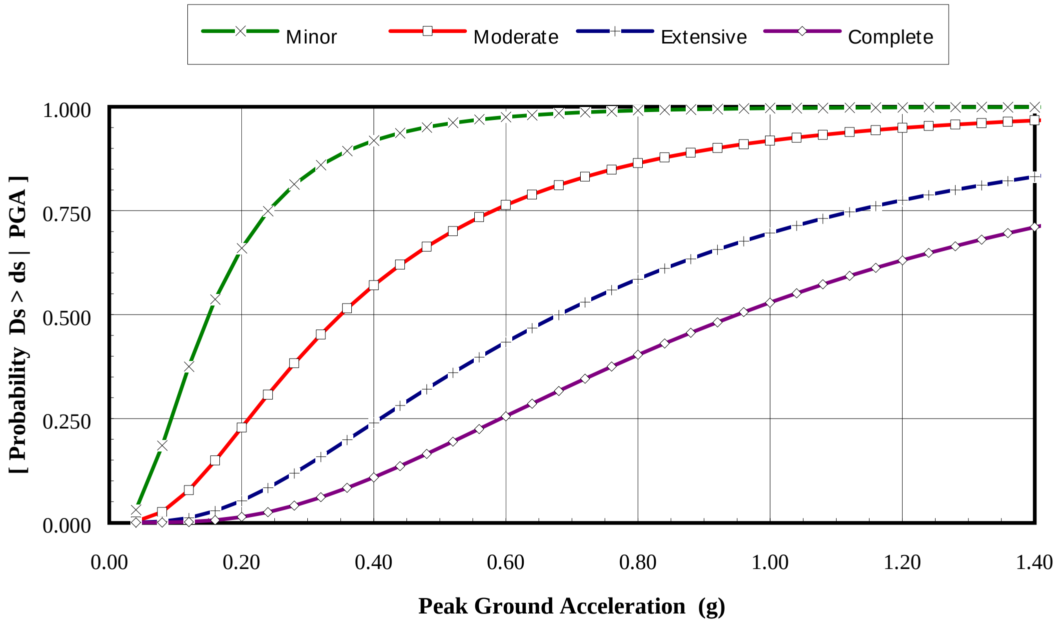


Figure 8.19: Fragility Curves for Unanchored On Ground Steel Tank.

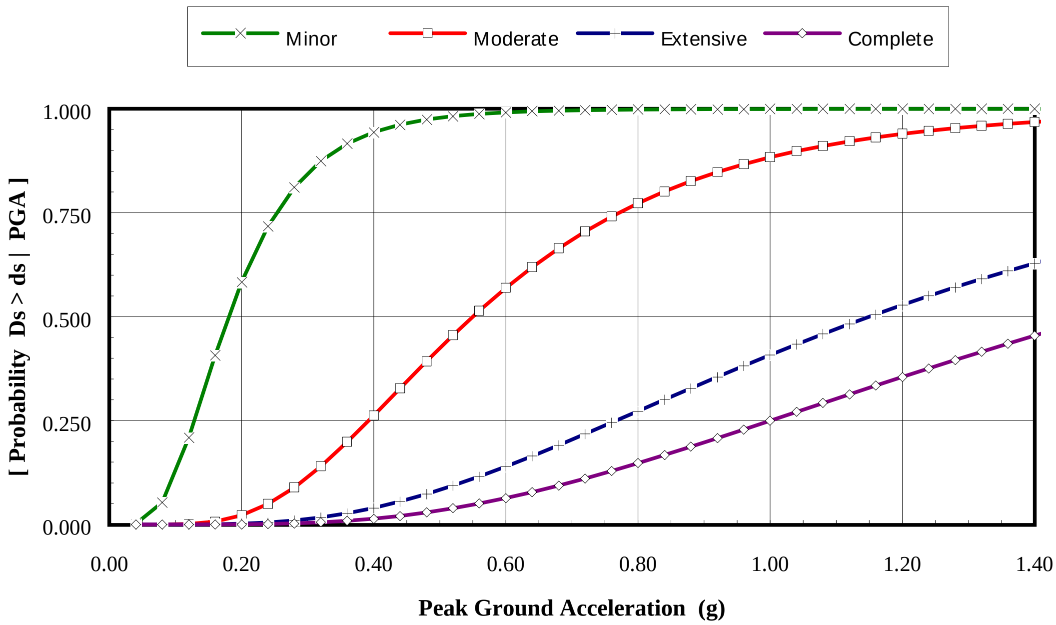


Figure 8.20: Fragility Curves for Above Ground Steel Tank.

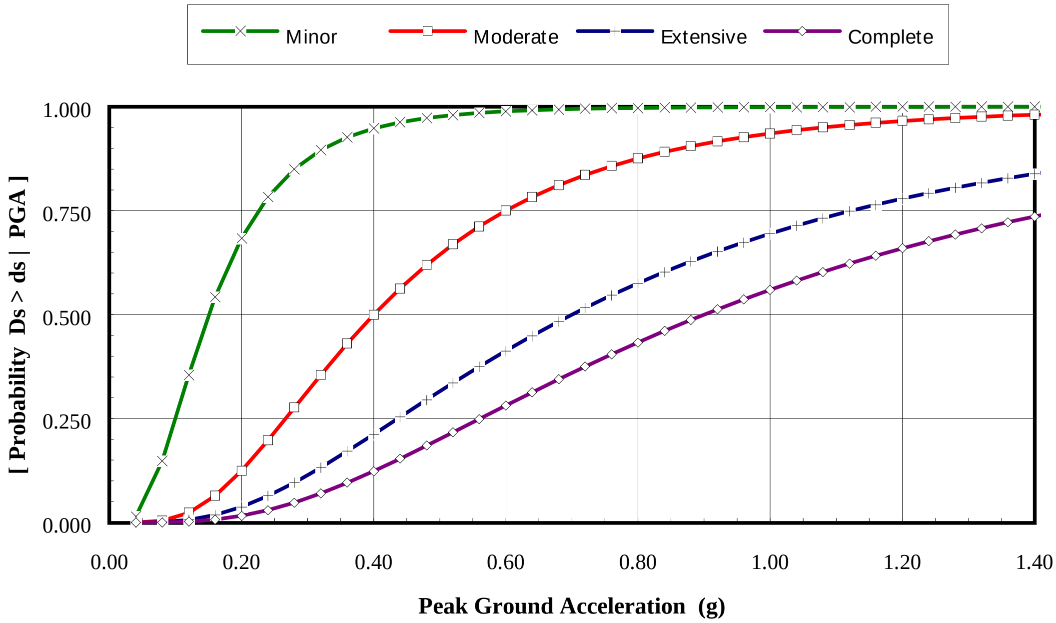


Figure 8.21: Fragility Curves for On Ground Wood Tank.

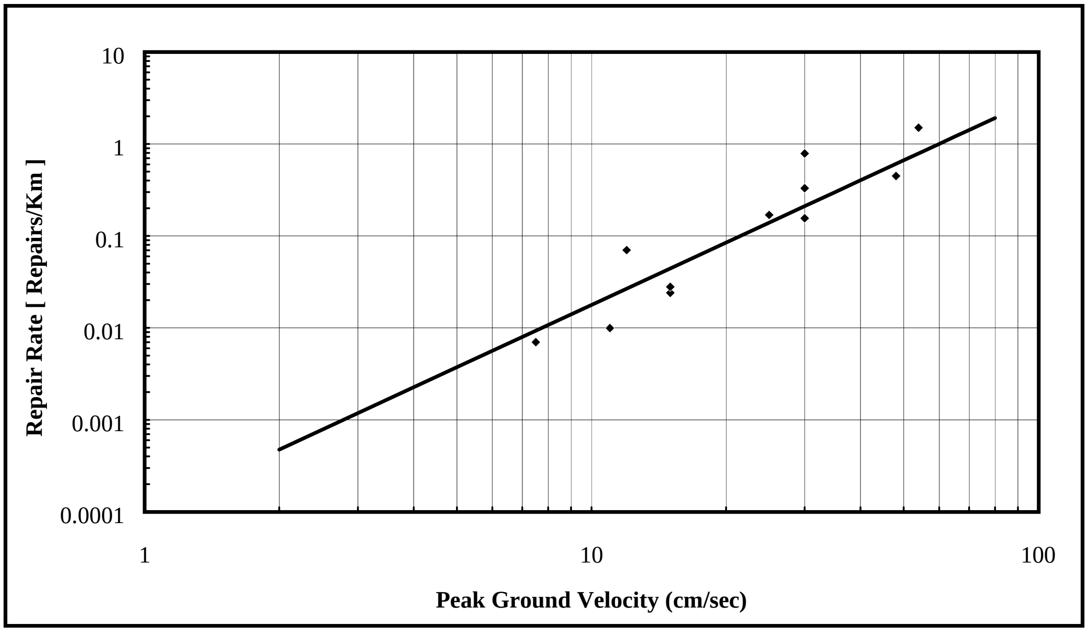


Figure 8.22.a: Ground Shaking (Wave Propagation) Damage Model for Brittle Pipes (Specifically CI, AC, RCC, and PCCP) Based on Four U.S. and Two Mexican Earthquakes (after O'Rourke and Ayala, 1993).

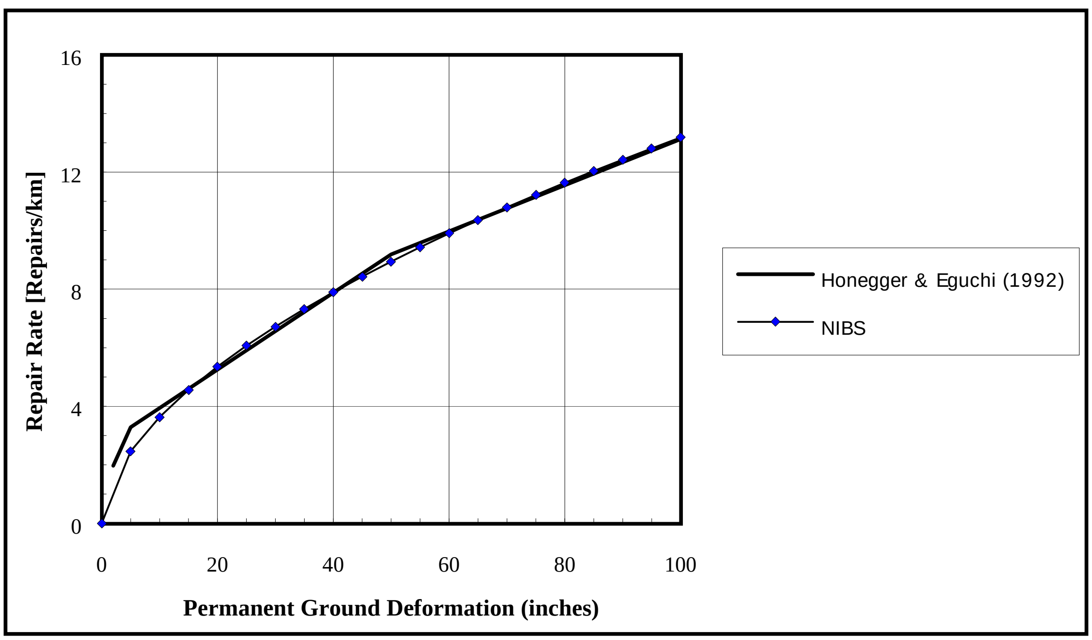


Figure 8.22.b: Ground Deformation Damage Model for Cast Iron Pipes (after Honegger and Eguchi, 1992).

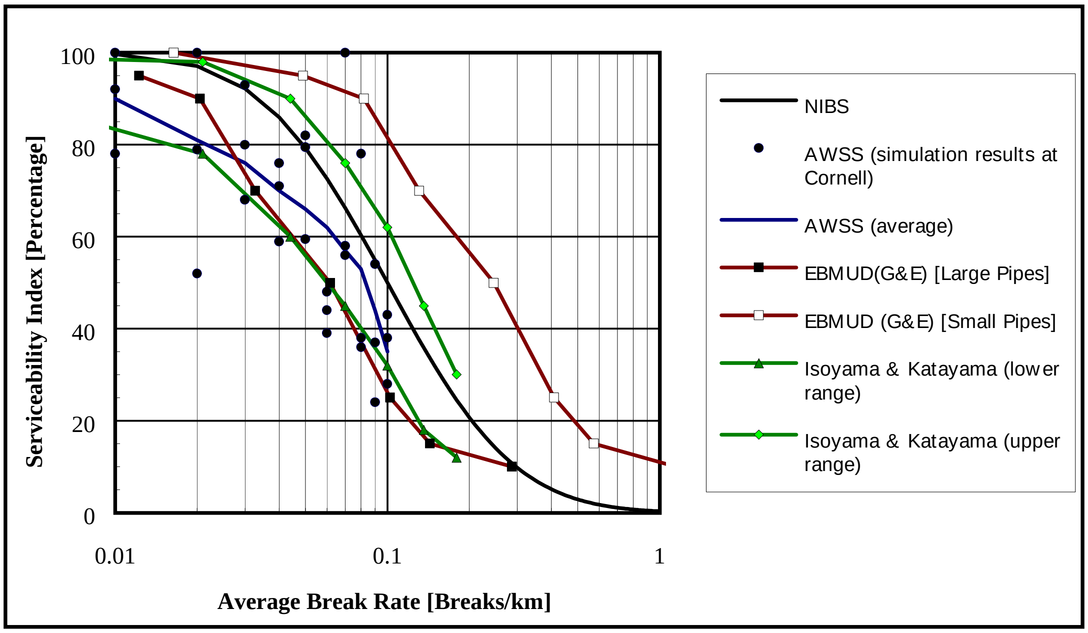


Figure 8.23: Damage Index Versus Average Break Rate for Post-Earthquake System Performance Evaluation.

8.2 Waste Water Systems

8.2.1 Introduction

This section presents a loss estimation methodology for a waste water system during earthquakes. This system consists of transmission, and treatment components. These components are vulnerable to damage during earthquakes, which may result in significant disruption to the utility network.

8.2.2 Scope

The scope of this section includes development of methods for estimation of earthquake damage to a waste water system given knowledge of components (i.e., underground sewers and interceptors, waste water treatment plants, and lift stations), classification (i.e., for waste water treatment plants, small, medium or large), and the ground motion (i.e., peak ground velocity, peak ground acceleration and/or permanent ground deformation). Damage states describing the level of damage to each of the waste water system components are defined (i.e., minor, moderate, extensive or complete for facilities plus #repairs/km for sewers/interceptors). Fragility curves are developed for each classification of water system component. These curves describe the probability of reaching or exceeding each damage state given the level of ground motion. Based on these fragility curves, a method for assessing functionality of each component of the waste water system is presented.

8.2.3 Input Requirements and Output Information

Required input to estimate damage to waste water systems is listed below.

Sewers and Interceptors

- Longitude and latitude of end nodes of links
- Peak ground velocity and permanent ground deformation (PGV and PGD)
- Classification

Waste Water Treatment Plant and Lift Stations

- Longitude and latitude of facility
- PGA and PGD
- Classification (small, medium or large, with anchored or unanchored components)

Direct damage output for waste water systems includes probability estimates of (1) component functionality and (2) damage, expressed in terms of the component's damage ratio (repair cost to replacement cost). Note that damage ratios for each of the waste water system components are presented in section 15.3 of Chapter 15.

8.2.4 Form of Damage Functions

Damage functions or fragility curves for waste water system components other than sewers and interceptors are modeled as lognormally-distributed functions that give the probability of reaching or exceeding different damage states for a given level of ground motion (quantified in terms of PGA) and ground failure (quantified in terms of PGD). Each of these fragility curves is characterized by a median value of ground motion (or failure) and an associated dispersion factor (lognormal standard deviation). For sewers and interceptors, empirical relations that give the expected repair rates due to ground motion (quantified in terms of PGV) or ground failure (quantified in terms of PGD) are provided.

Definitions of various damage states and the methodology used in deriving all these fragility curves are presented in the next section.

8.2.5 Description of Waste Water System Components

As mentioned before, a waste water system typically consists of collection sewers, interceptors, lift stations, and wastewater treatment plants. In this section, a brief description of each of these components is given.

Collection Sewers

Collection sewers are generally closed conduits that carry normally sewage with a partial flow. Collection sewers could be sanitary sewers, storm sewers, or combined sewers. Pipe materials that are used for potable water transportation may also be used for wastewater collection. The most commonly used sewer material is clay pipe manufactored with integral bell and spigot end. These pipes range in size from 4 to 42 inches in diameter. Concrete pipes are mostly used for storm drains and for sanitary sewers carrying noncorrosive sewage (i.e. with organic materials). For the smaller diameter range, plastic pipes are also used.

Interceptors

Interceptors are large diameter sewer mains. They are usually located at the lowest elevation areas. Pipe materials that are used for interceptor sewers are similar to those used for collection sewers.

Lift Stations (LS)

Lift stations are important parts of the waste water system. Lift stations serve to raise sewage over topographical rises. If the lift station is out of service for more than a short time, untreated sewage will either spill out near the lift station, or back up into the collection sewer system.

In this study, lift stations are classified as either small LS (capacity less than 10 mgd) or medium/large LS (capacity greater than 10 mgd). Lift stations are also classified as having either anchored or unanchored subcomponents (see section 7.2.5 for the definition of anchored and unanchored subcomponents)

Waste Water Treatment Plants (WWTP)

Three sizes of wastewater treatment plants are considered: small (capacity less than 50 mgd), medium (capacity between 50 and 200 mgd), and large (capacity greater than 200 mgd). WWTP has the same processes existing in WTP with the addition of secondary treatment subcomponents.

8.2.6 Definitions of Damage States

Waste water systems are susceptible to earthquake damage. Facilities such as waste water treatment plants and lift stations are mostly vulnerable to PGA, and sometimes PGD, if located in liquefiable or landslide zones. Therefore, the damage states for these components are defined and associated with PGA and PGD. Sewers, on the other hand, are vulnerable to PGV and PGD. Therefore, the damage algorithms for these components are associated with those two ground motion parameters.

8.2.6.1 Damage States Definitions for Components other than Sewers/Interceptors

A total of five damage states are defined for waste water system components other than sewers and interceptors. These are none (ds_1), slight/minor (ds_2), moderate (ds_3), extensive (ds_4) and complete (ds_5).

Slight/Minor Damage (ds_2)

- **For waste water treatment plants**, ds_2 is defined as for WTP in potable water systems.
- **For lift stations**, ds_2 is defined as for pumping plants in potable water systems.

Moderate Damage (ds_3)

- **For waste water treatment plants**, ds_3 is defined as for WTP in potable water systems.
- **For lift stations**, ds_3 is defined as for pumping plants in potable water systems.

Extensive Damage (ds_4)

- **For waste water treatment plants**, ds_4 is defined as for WTP in potable water systems.

- **For lift stations**, ds_4 is defined as for pumping plants in potable water systems.

Complete Damage (ds_5)

- **For waste water treatment plants**, ds_5 is defined as for WTP in potable water systems.

- **For lift stations**, ds_5 is defined as for pumping plants in potable water systems.

8.2.6.2 Damage States Definitions for Sewers/Interceptors

For sewers/interceptors, two damage states are considered. These are leaks and breaks. Generally, when a sewer/interceptor is damaged due to ground failure, the type of damage is likely to be a break, while when a sewer/interceptor is damaged due to seismic wave propagation; the type of damage is likely to be joint pullout or crushing at the bell. In the loss methodology, it is assumed that damage due to seismic waves will consist of 80% leaks and 20% breaks, while damage due to ground failure will consist of 20% leaks and 80% breaks. The user can override these default percentages.

8.2.7 Component Restoration Curves

The restoration curves for waste water system components are based on ATC-13 expert data (SF-31.a through SF-331.c). Restoration data for lift stations, and wastewater treatment plants, in the form of dispersions of the restoration functions, are given in Table 8.12.a. The restoration functions are shown in Figures 8.24 and 8.25. Figure 8.24 represents the restoration functions for lift stations and Figure 8.25 represents the restoration curves for wastewater treatment plants. The discretized restoration functions are presented in Table 8.12.b, where the restoration percentage is shown at discretized times. Restoration for sewers follows the same approach for potable water pipelines, presented in section 8.1.7 .

Table 8.12.a: Restoration Functions for Waste Water System Components

Restoration Functions (All Normal Distributions)			
Classification	**Damage State**	**Mean (Days)**	**σ**
Lift Stations	slight/minor	1.3	0.7
	moderate	3.0	1.5
	extensive	21.0	12.0
	complete	65.0	25.0
Waste Water Treatment Plants	slight/minor	1.5	1.0
	moderate	3.6	2.5
	extensive	55.0	25.0
	complete	160.0	60.0
Sewers/Interceptors	See Section 8.1.7		

Table 8.12.b: Discretized Restoration Functions for Waste Water System Components

Discretized Restoration Functions						
Classification	**Damage State**	**1 day**	**3 days**	**7 days**	**30 days**	**90 days**
Lift Stations	slight/minor	34	100	100	100	100
	moderate	10	50	100	100	100
	extensive	5	7	13	78	100
	complete	0	1	2	9	85
Waste Water Treatment Plants	slight/minor	31	94	100	100	100
	moderate	15	40	92	100	100
	extensive	2	2	3	16	92
	complete	1	1	1	2	13
Sewers/Interceptors	See Section 8.1.7					

8.2.8 Development of Damage Functions

In this subsection, damage functions for the various components of a waste water system are presented. In cases where the components are made of subcomponents (i.e., waste water treatment plants and lift stations), fragility curves for these components are based on the probabilistic combination of subcomponent damage functions using Boolean expressions to describe the relationship of subcomponents. The Boolean logic is implicitly presented within the definition of a particular damage state (see section 8.1.8 for an example).

Damage functions due to ground failure (i.e., PGD) for waste water treatment plants and lift stations are assumed to be similar to those described for potable water system facilities in section 8.1.8.

Damage Functions for Lift Stations

Damage functions for lift stations are similar to those of pumping plants in potable water systems described in Section 8.1.8.

Damage Functions for Waste Water Treatment Plants (due to Ground Shaking)

Tables 8.13 through 8.15 present damage functions for small, medium and large wastewater treatment plants, respectively. Graphical representations of wastewater treatment plant damage functions are shown in Figures 8.26 through 8.31. The medians and dispersions of damage functions to waste water treatment plants subcomponents are summarized in Tables B.8.1 and B.8.2 of Appendix 8B.

Table 8.13: Damage Algorithms for Small Waste Water Treatment Plants

Peak Ground Acceleration			
Classification	**Damage State**	**Median (g)**	**β**
Plants with anchored components (WWT1)	slight/minor	0.23	0.40
	moderate	0.35	0.40
	extensive	0.48	0.50
	complete	0.80	0.55
Plants with unanchored components (WWT2)	slight/minor	0.16	0.40
	moderate	0.26	0.40
	extensive	0.48	0.50
	complete	0.80	0.55

Table 8.14: Damage Algorithms for Medium Waste Water Treatment Plants

Peak Ground Acceleration			
Classification	**Damage State**	**Median (g)**	**β**
Plants with anchored components (WWT3)	slight/minor	0.33	0.40
	moderate	0.49	0.40
	extensive	0.70	0.45
	complete	1.23	0.55
Plants with unanchored components (WWT4)	slight/minor	0.20	0.40
	moderate	0.33	0.40
	extensive	0.70	0.45
	complete	1.23	0.55

Table 8.15: Damage Algorithms for Large Waste Water Treatment Plants

Peak Ground Acceleration			
Classification	**Damage State**	**Median (g)**	**β**
Plants with anchored components (WWT5)	slight/minor	0.40	0.40
	moderate	0.56	0.40
	extensive	0.84	0.40
	complete	1.50	0.40
Plants with unanchored components (WWT6)	slight/minor	0.22	0.40
	moderate	0.35	0.40
	extensive	0.84	0.40
	complete	1.50	0.40

Damage Functions for Sewers and Interceptors

The same two damage algorithms proposed for buried pipelines in potable water systems are assumed to apply for sewers and interceptors. These are listed again in Table 8.16. Note that R.R. stands for repair rates or number of repairs per kilometer, PGV stands for peak ground velocity in cm/sec, and PGD stands for permanent ground deformation in inches.

Table 8.16: Damage Algorithms for Sewers/Interceptors

	PGV Algorithm		**PGD Algorithm**	
	R. R. $\cong$ 0.0001 x PGV$^{(2.25)}$		R. R. $\cong$ Prob[liq]xPGD$^{(0.56)}$	
Pipe Type	Multiplier	Example of Pipe	Multiplier	Example of Pipe
Brittle Sewers/Interceptors (WWP1)	1	Clay, Concrete	1	Clay, Concrete
Ductile Sewers/Interceptors (WWP2)	0.3	Plastic	0.3	Plastic

8.2.9 Guidance for Loss Estimation with Advanced Data and Models Analysis

For this type of analysis, the expert can use the methodology developed with the flexibility to (1) include a more refined inventory of the waste water system pertaining to the area of study, and (2) include component-specific and system-specific fragility data. Default damage algorithms for User-Supplied Data Analysis, can be modified or replaced to incorporate improved information about key components of a waste water system. Similarly, better restoration curves can be developed, given knowledge of available resources and a more accurate layout of the wastewater network within the local topographic and geological conditions.

8.2.10 References

(1) ATC-13, "Earthquake Damage Evaluation Data for California", Applied Technology Council, Redwood City, CA, 1985.

(2) G&E Engineering Systems, Inc. (G&E), "NIBS Earthquake Loss Estimation Methods, Technical Manual, (Waste Water Systems)", June 1994.

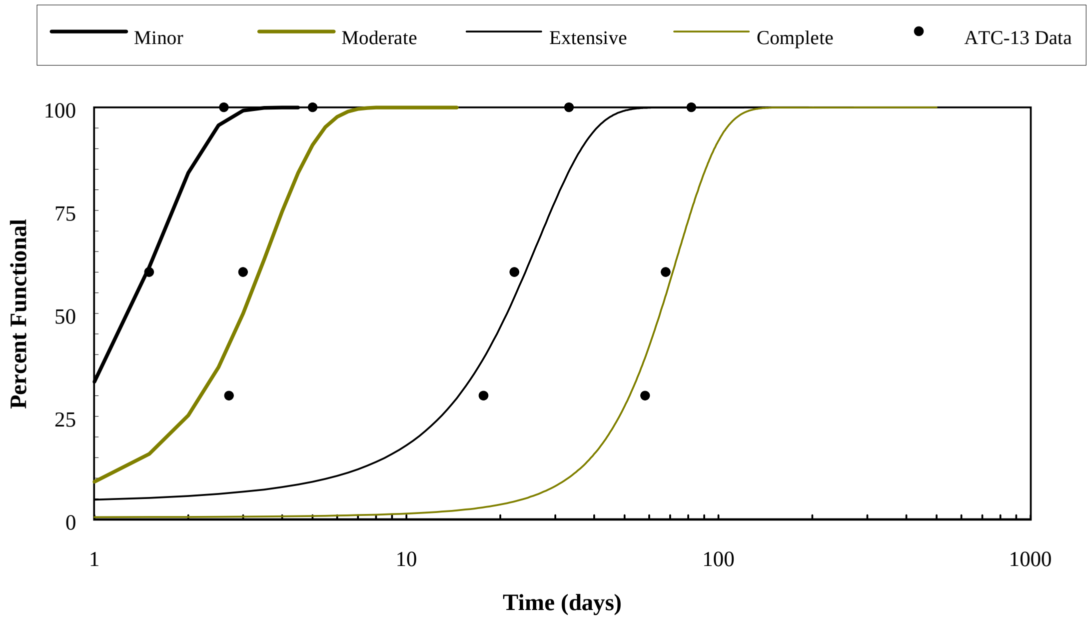


Figure 8.24: Restoration Curves for Lift Stations.

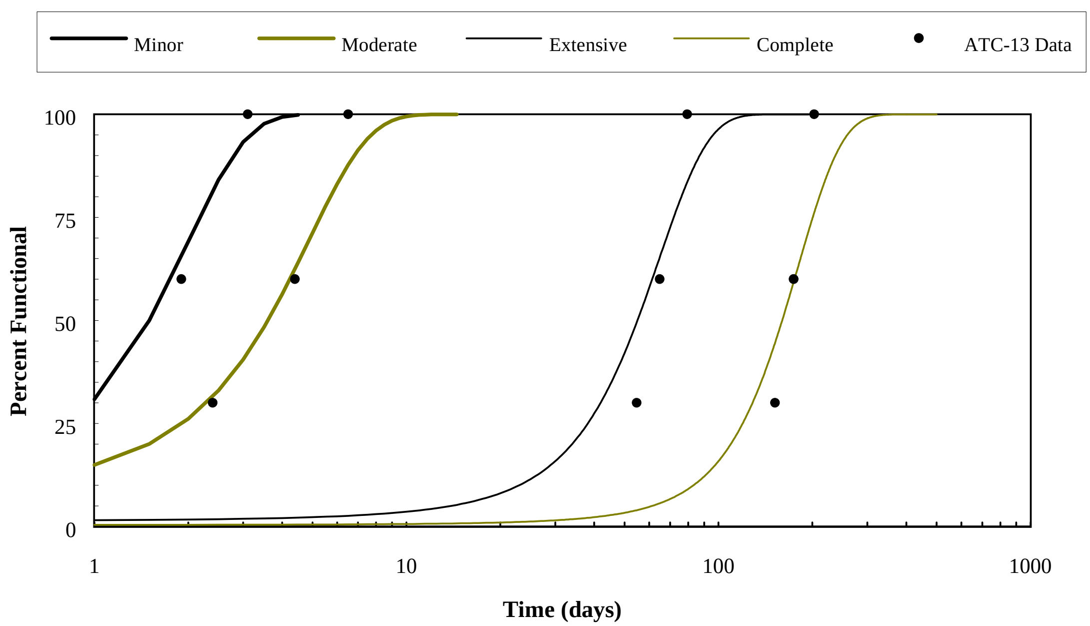


Figure 8.25: Restoration Curves for Waste Water Treatment Plants.

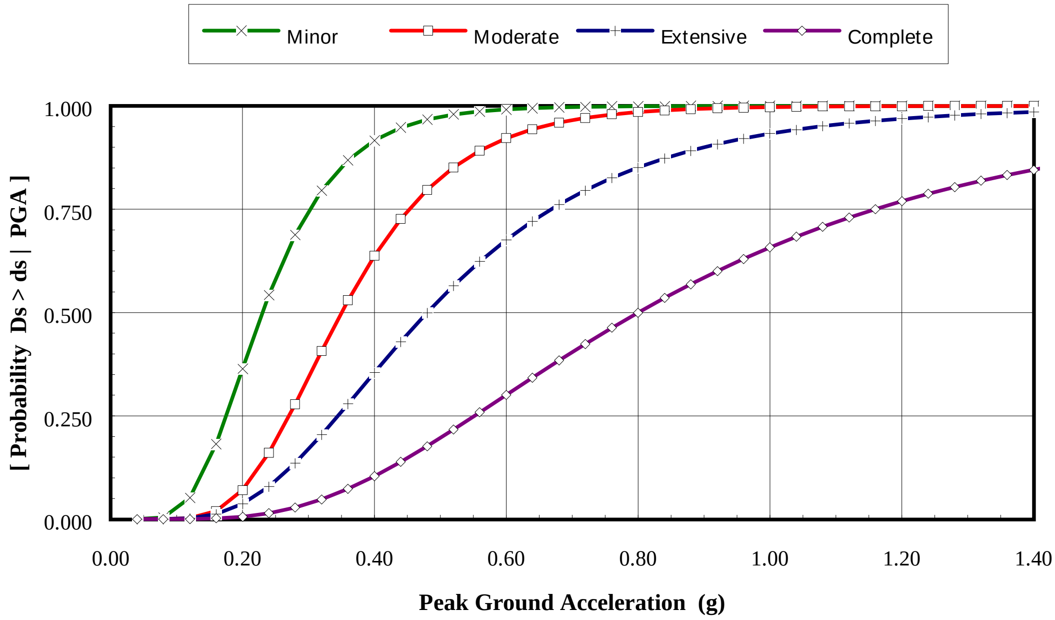


Figure 8.26: Fragility Curves for Small Waste Water Treatment Plants with Anchored Components.

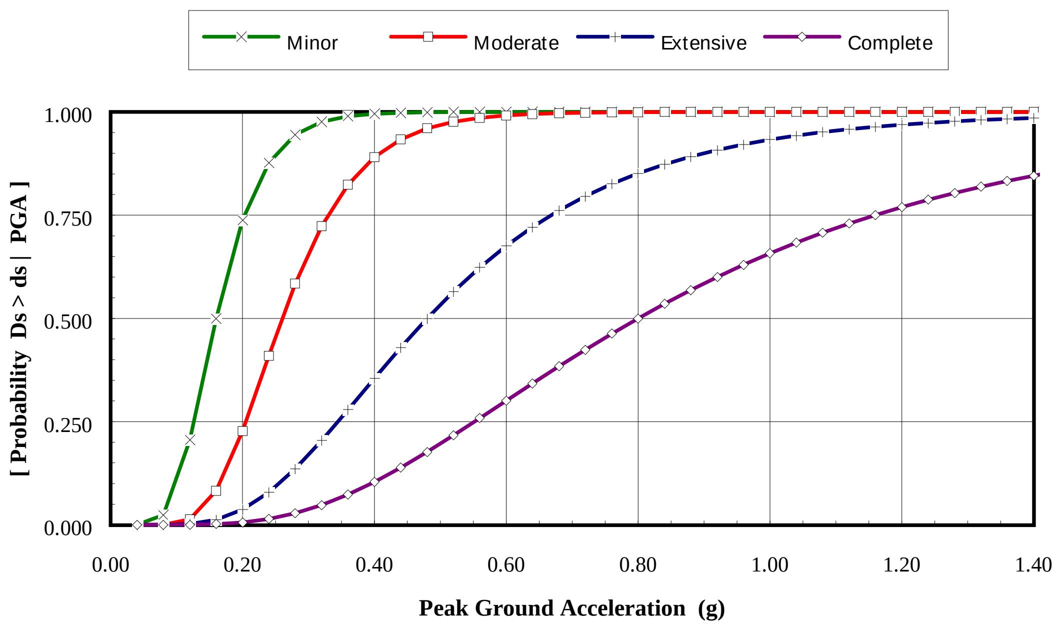


Figure 8.27: Fragility Curves for Small Waste Water Treatment Plants with Unanchored Components.

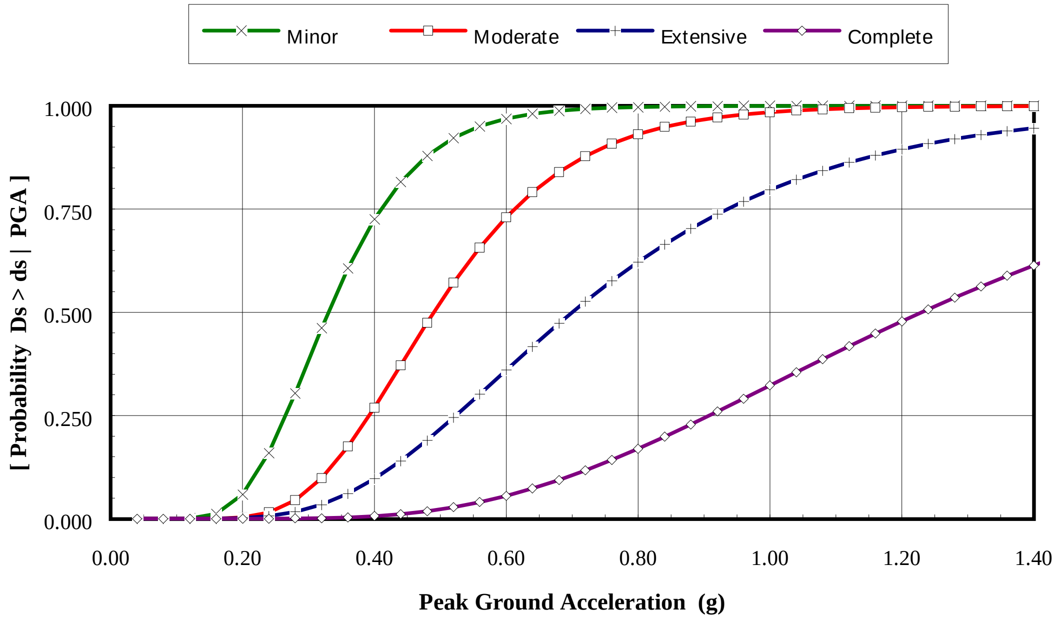


Figure 8.28: Fragility Curves for Medium Waste Water Treatment Plants with Anchored Components.

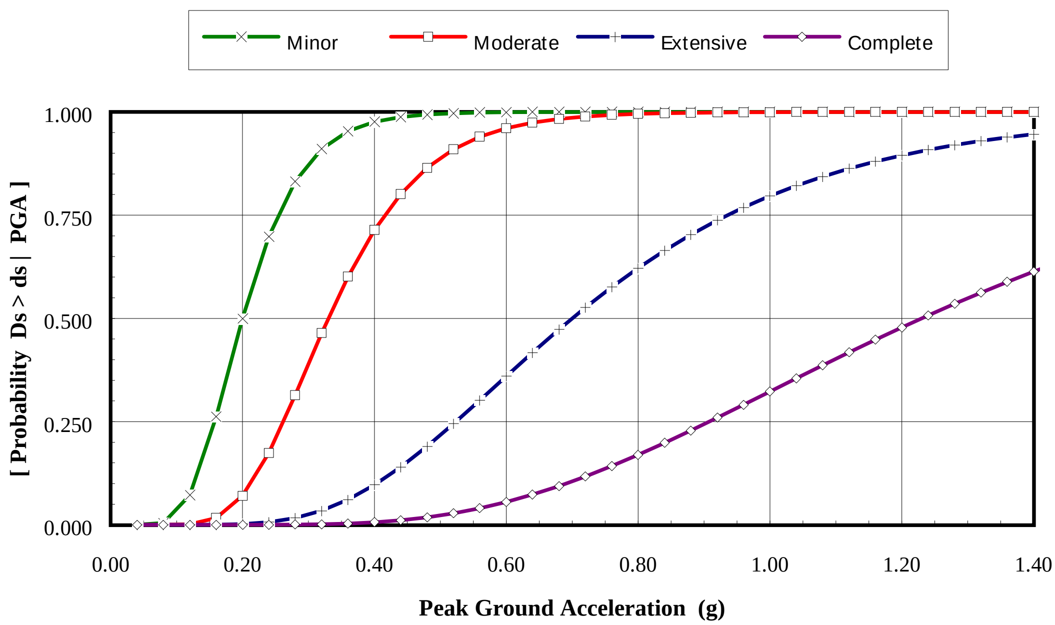


Figure 8.29: Fragility Curves for Medium Waste Water Treatment Plants with Unanchored Components.

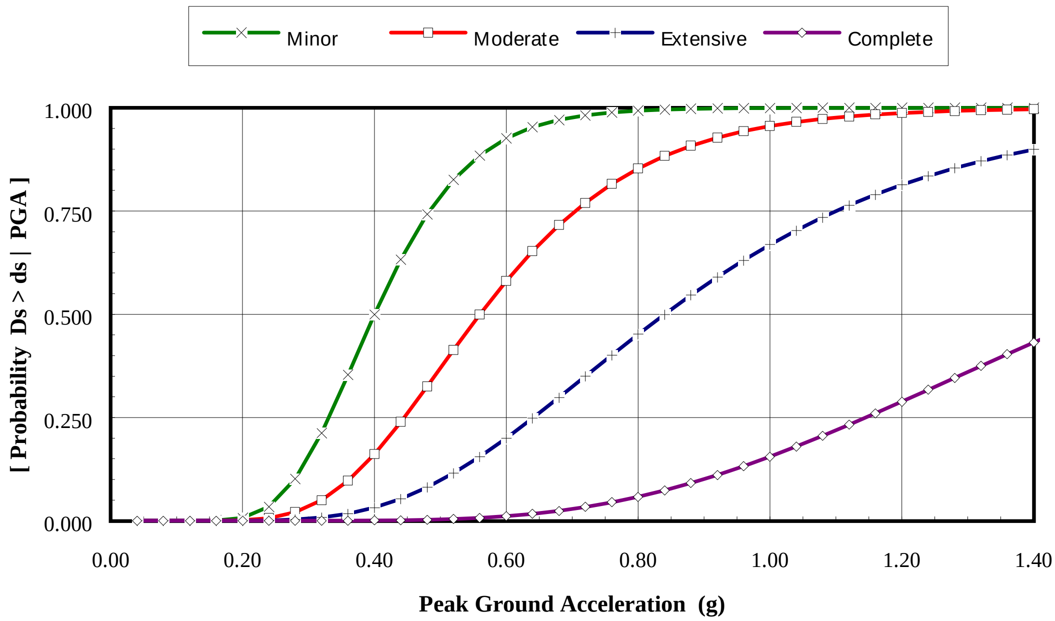


Figure 8.30: Fragility Curves for Large Waste Water Treatment Plants with Anchored Components.

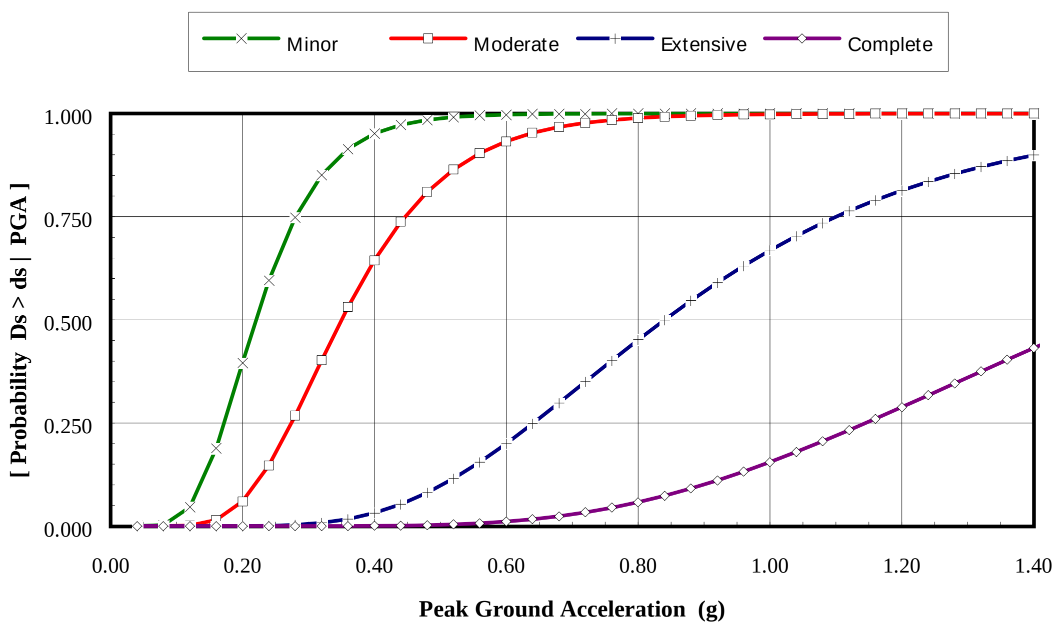


Figure 8.31: Fragility Curves for Large Waste Water Treatment Plants with Unanchored Components.

8.3 Oil Systems

8.3.1 Introduction

This section presents a loss estimation methodology for an oil system during earthquakes. This system consists of refineries and transmission components. These components are vulnerable to damage during earthquakes, which may result in significant disruption to this utility network.

8.3.2 Scope

The scope of this section includes development of methods for estimation of earthquake damage to an oil system given knowledge of components (i.e. refineries, pumping plants, and tank farms), classification (i.e. for refineries, with anchored or unanchored components), and the ground motion (i.e. peak ground velocity, peak ground acceleration and/or permanent ground deformation). Damage states describing the level of damage to each of the oil system components are defined (i.e. minor, moderate, extensive or complete, plus # repairs/km for pipelines). Fragility curves are developed for each classification of the oil system component. These curves describe the probability of reaching or exceeding each damage state given the level of ground motion.

Based on these fragility curves, a method for assessing functionality of each component of the oil system is presented.

8.3.3 Input Requirements and Output Information

Required input to estimate damage to oil described are listed below.

Refineries, Pumping Plants and Tank Farms

- Longitude and latitude of facility
- PGA and PGD
- Classification (small, medium/large, with anchored or unanchored components)

Oil Pipelines

- Geographical location of pipe links (longitude and latitude of end nodes)
- Peak ground velocity and permanent ground deformation (PGV and PGD)
- Classification

Direct damage output for oil systems includes probability estimates of (1) component functionality and (2) damage, expressed in terms of the component's damage ratio (repair cost to replacement cost). Note that damage ratios for each of the oil system components are presented in section 15.3 of Chapter 15.

8.3.4 Form of Damage Functions

Damage functions or fragility curves for oil system components other than pipelines are modeled as lognormally-distributed functions that give the probability of reaching or exceeding different damage states for a given level of ground motion (quantified in terms of PGA) and ground failure (quantified in terms of PGD). Each of these fragility curves is characterized by a median value of ground motion (or failure) and an associated dispersion factor (lognormal standard deviation). For oil piplines, empirical relations that give the expected repair rates due to ground motion (quantified in terms of PGV) or ground failure (quantified in terms of PGD) are provided.

Definitions of various damage states and the methodology used in deriving all these fragility curves are presented in the next section.

8.3.5 Description of Oil System Components

As mentioned before, an oil system typically consists of refineries, pumping plants, tank farms, and pipelines. In this section, a brief description of each of these components is given.

Refineries (RF)

Refineries are an important part of an oil system. They are used for processing crude oil before it can be used. Although supply of water is critical to the functioning of refinery, it is assumed in the methodology that an uninterrupted supply of water is available to the refinery. Two sizes of refineries are considered: small, and medium/large.

Small refineries (capacity less than 100,000 barrels per day), are assumed to consist of steel tanks on grade, stacks, other electrical and mechanical equipment, and elevated pipes. Stacks are essentially tall cylindrical chimneys.

Medium/Large refineries (capacity more than 100,000 barrels per day), are simulated by adding more redundancy to small refineries (i.e. twice as many tanks, stacks, elevated pipes).

Oil Pipelines

Oil pipelines are used for the transportation of oil over long distances. About seventy-five percent of the crude oil is transported throughout the United States by pipelines. A large segment of industry and millions of people could be severely affected by disruption of crude oil supplies. Rupture of crude oil pipelines could lead to pollution of land and rivers. Pipelines are typically made of mild steel with submerged arc welded joints, although older gas welded steel pipe may be present in some systems. In this sudy, buried pipelines are considered to be vulnerable to PGV and PGD.

Pumping Plants (PP)

Pumping plants serve to maintain the flow of oil in cross-country pipelines. Pumping plants usually use two or more pumps. Pumps can be of either centrifugal or reciprocating type. However, no differentiation is made between these two types of pumps in the analysis of oil systems. Pumping plants are classified as having either anchored or unanchored subcomponents, as defined in 7.2.5.

Tank Farms (TF)

Tank farms are facilities that store fuel products. They include tanks, pipes and electric components. Tank farms are classified as having either anchored or unanchored subcomponents, as defined in 7.2.5.

8.3.6 Definitions of Damage States

Oil systems are susceptible to earthquake damage. Facilities such as refineries, pumping plants and tank farms are mostly vulnerable to PGA, and sometimes PGD, if located in liquefiable or landslide zones. Therefore, the damage states for these components are defined and associated with PGA and PGD. Pipelines, on the other hand, are vulnerable to PGV and PGD. Therefore, the damage states for these components are associated with these two ground motion parameters.

8.3.6.1 Damage States Definitions for Components other than Pipelines

A total of five damage states are defined for oil system components other than pipelines. These are none (ds_1), slight/minor (ds_2), moderate (ds_3), extensive (ds_4) and complete (ds_5).

Slight/Minor Damage (ds_2)

- **For refineries**, ds_2 is defined by malfunction of plant for a short time (few days) due to loss of electric power and backup power, if any, or light damage to tanks.

- **For pumping plants**, ds_2 is defined by light damage to building.

- **For tank farms**, ds_2 is defined by malfunction of plant for a short time (less than three days) due to loss of backup power or light damage to tanks.

<u>Moderate Damage</u> (ds_3)

- **<u>For refineries</u>**, ds_3 is defined by malfunction of plant for a week or so due to loss of electric power and backup power if any, extensive damage to various equipment, or considerable damage to tanks.

- **<u>For pumping plants</u>**, ds_3 is defined by considerable damage to mechanical and electrical equipment, or considerable damage to building.

- **<u>For tank farms</u>**, ds_3 is defined by malfunction of tank farm for a week or so due to loss of backup power, extensive damage to various equipment, or considerable damage to tanks.

<u>Extensive Damage</u> (ds_4)

- **<u>For refineries</u>**, ds_4 is defined by the tanks being extensively damaged, or stacks collapsing.

- **<u>For pumping plants</u>**, ds_4 is defined by the building being extensively damaged, or pumps badly damaged.

- **<u>For tank farms</u>**, ds_4 is defined by the tanks being extensively damaged, or extensive damage to elevated pipes.

<u>Complete Damage</u> (ds_5)

- **<u>For refineries</u>**, ds_5 is defined by the complete failure of all elevated pipes, or collapse of tanks.

- **<u>For pumping plants</u>**, ds_5 is defined by the building being in complete damage state.

- **<u>For tank farms</u>**, ds_5 is defined by the complete failure of all elevated pipes, or collapse of tanks.

8.3.6.2 Damage State Definitions for Pipelines

For pipelines, two damage states are considered. These are leaks and breaks. Generally, when a pipe is damaged due to ground failure, the type of damage is likely to be a break, while when a pipe is damaged due to seismic wave propagation; the type of damage is likely to be local buckling of the pipe walll. In the loss methodology, it is assumed that damage due to seismic waves will consist of 80% leaks and 20% breaks, while damage due to ground failure will consist of 20% leaks and 80% breaks. The user can override these default percentages.

8.3.7 Component Restoration Curves

The restoration curves for the oil system are obtained using the data for mean restoration time from ATC-13. The restoration functions for pumping plants are similar to those of pumping plants in potable water system. The data for refineries and tank farms are based on SF-18b and SF-18d of ATC-13. Means and standard deviations of the restoration functions are given in Table 8.17.a. The restoration functions are shown in Figures 8.32 through 8.34. Figure 8.32 represents the restoration functions for refineries, Figure 8.33 represents the restoration curves for tank farms, and Figure 8.34 represents the restoration curves for buried pipes. The discretized restoration functions are presented in Table 8.17.b, where the restoration percentage is given at discretized times. Restoration for oil pipelines follows the same approach for potable water pipelines, presented in section 8.1.7 .

Table 8.17.a: Restoration Functions for Oil System Components

Restoration Functions (All Normal Distributions)			
Classification	**Damage State**	**Mean (Days)**	**σ**
Refineries	slight/minor	0.4	0.1
	moderate	3.0	2.2
	extensive	14.0	12.0
	complete	190.0	80.0
Tank Farms	slight/minor	0.9	0.5
	moderate	7.0	7.0
	extensive	28.0	26.0
	complete	70.0	55.0
Pipelines	See section 8.1.7		

Table 8.17.b: Discretized Restoration Functions for Oil System Components

Discretized Restoration Functions						
Classification	**Damage State**	**1 day**	**3 days**	**7 days**	**30 days**	**90 days**
Refineries	slight/minor	100	100	100	100	100
	moderate	19	50	97	100	100
	extensive	14	18	28	91	100
	complete	0	1	2	3	11
Tank Farms	slight/minor	58	100	100	100	100
	moderate	20	29	50	100	100
	extensive	15	17	21	54	100
	complete	11	12	13	24	65
Pipelines	See section 8.1.7					

8.3.8 Development of Damage Functions

In this subsection, damage functions for the various components of a refined or a crude oil system are presented. In cases where the components are made of subcomponents (i.e., refineries, tank farms and pumping plants), fragility curves for these components are based on the probabilistic combination of subcomponent damage functions using Boolean expressions to describe the relationship of subcomponents. It should be mentioned that the Boolean logic is implicitly presented within the definition of a particular damage state (see section 8.1.8 for an example).

It should be mentioned that damage functions due to ground failure (i.e., PGD) for refineries, tank farms and pumping plants are assumed to be similar to those described for potable water system facilities in section 8.1.8.

Damage Functions for Refineries (due to Ground Shaking)

PGA related damage functions for refineries are developed with respect to classification. Tables 8.18.a and 8.18.b present damage functions for small and medium/large refineries, respectively. These fragility curves are also plotted in Figures 8.35 through 8.38. The medians and dispersions of damage functions to refinery subcomponents are summarized in Tables C.8.1 and C.8.2 of Appendix 8C.

Table 8.18.a: Damage Algorithms for Small Refineries (Capacity < 100,000 barrels/day)

Peak Ground Acceleration			
Classification	**Damage State**	**Median (g)**	**β**
Refineries with anchored components (ORF1)	slight/minor	0.29	0.55
	moderate	0.52	0.50
	extensive	0.64	0.60
	complete	0.86	0.55
Refineries with unanchored components (ORF2)	slight/minor	0.13	0.50
	moderate	0.27	0.50
	extensive	0.43	0.60
	complete	0.68	0.55

Table 8.18.b: Damage Algorithms for Medium/Large Refineries (Capacity ≥ 100,000 barrels/day)

Peak Ground Acceleration			
Classification	**Damage State**	**Median (g)**	**β**
Refineries with anchored components (ORF3)	slight/minor	0.38	0.45
	moderate	0.60	0.45
	extensive	0.98	0.50
	complete	1.26	0.45
Refineries with unanchored components (ORF4)	slight/minor	0.17	0.40
	moderate	0.32	0.45
	extensive	0.68	0.50
	complete	1.04	0.45

Damage Functions for Pumping Plants (due to Ground Shaking)

PGA related damage functions for pumping plants are also developed with respect to classification and ground motion parameter and are presented in Table 8.19. These damage functions are also plotted in Figures 8.39 and 8.40. The medians and dispersions of pumping plants subcomponent damage functions are summarized in Tables C.8.3 and C.8.4 of Appendix 8C.

Table 8.19: Damage Algorithms for Pumping Plants

Peak Ground Acceleration			
Classification	**Damage State**	**Median (g)**	**β**
Plants with anchored components (OPP1)	slight/minor	0.15	0.75
	moderate	0.34	0.65
	extensive	0.77	0.65
	complete	1.50	0.80
Plants with unanchored components (OPP2)	slight/minor	0.12	0.60
	moderate	0.24	0.60
	extensive	0.77	0.65
	complete	1.50	0.80

Damage Functions for Tank Farms (due to Ground Shaking)

PGA related damage functions for tank farms are developed with respect to classification and ground motion parameter. These damage functions are given in terms of median values and dispersions corresponding each damage state in Table 8.20. The fragility curves are plotted in Figures 8.41 and 8.42. The medians and dispersions of tank farms subcomponent damage functions are presnted in Appendix 8C.

Table 8.20: Damage Algorithms for Tank Farms

Peak Ground Acceleration			
Classification	**Damage State**	**Median (g)**	**β**
Plants with anchored components (OTF1)	slight/minor	0.29	0.55
	moderate extensive	0.50	0.55
	complete	0.87	0.50
Plants with unanchored components (OTF2)	slight/minor	0.12	0.55
	moderate	0.23	0.55
	extensive	0.41	0.55
	complete	0.68	0.55

<u>Damage Functions for Oil Pipelines</u>

The same two damage algorithms proposed for potable water pipelines are assumed to apply for crude and refined oil pipelines. These are listed again in Table 8.21. Note that mild steel pipelines with submerged arc welded joints are classfied as ductile pipes, while the older gas welded steel pipelines, if any, are classifed as brittle pipes. In Table 8.21, R.R. stands for repair rates or number of repairs per kilometer, PGV stands for peak ground velocity in cm/sec, and PGD stands for permanent ground deformation in inches.

Table 8.21: Damage Algorithms for Oil Pipelines

	PGV Algorithm		**PGD Algorithm**	
	R. R. ≅ 0.0001 x PGV$^{(2.25)}$		R. R. ≅ Prob[liq]xPGD$^{(0.56)}$	
Pipe Type	Multiplier	Example of Pipe	Multiplier	Example of Pipe
Brittle Oil Pipelines (OIP1)	1	Steel Pipe w/ GasWJ	1	Steel Pipe w/ GasWJ
Ductile Oil Pipelines (OIP2)	0.3	Steel Pipe w/ ArcWJ	0.3	Steel Pipe w/ ArcWJ

8.3.9 Guidance for Loss Estimation with Advanced Data and Models

For this type of analysis, the expert can use the methodology developed with the flexibility to (1) include a more refined inventory of the oil system pertaining to the area of study, and (2) include component-specific and system-specific fragility data. Default damage algorithms for User-Supplied Data Analysis, can be modified or replaced to incorporate improved information about key components of an oil system. Similarly, better restoration curves can be developed, given knowledge of available resources.

8.3.10 References

(1) ATC-13, "Earthquake Damage Evaluation Data for California", Applied Technology Council, Redwood City, CA, 1985.

(2) G&E Engineering Systems, Inc. (G&E), "NIBS Earthquake Loss Estimation Methods, Technical Manual, (Fuel Systems)", June 1994.

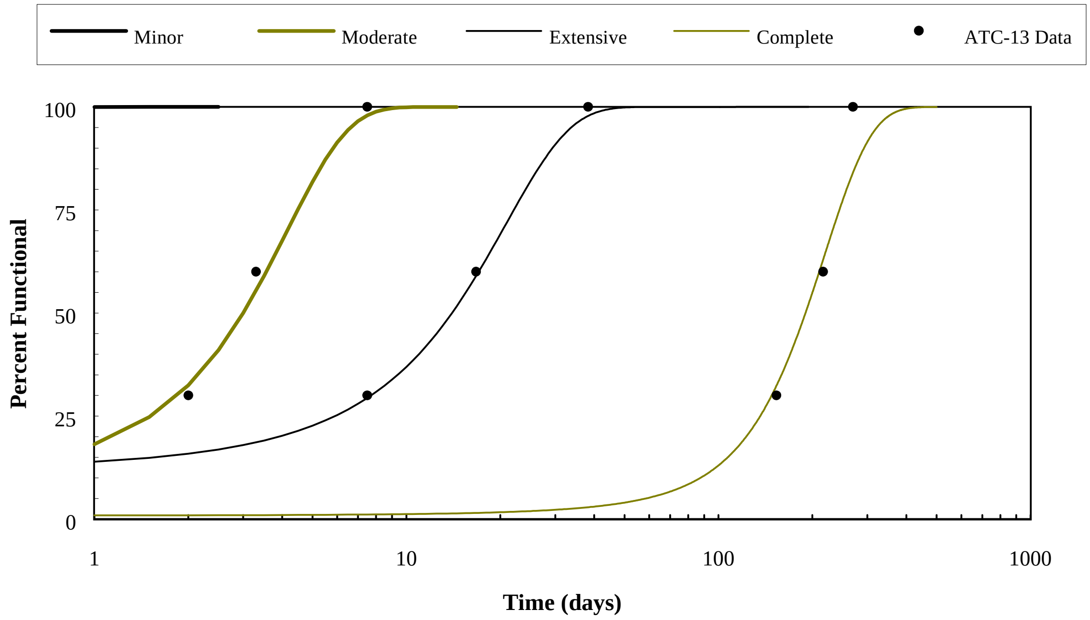


Figure 8.32: Restoration Curves for Refineries.

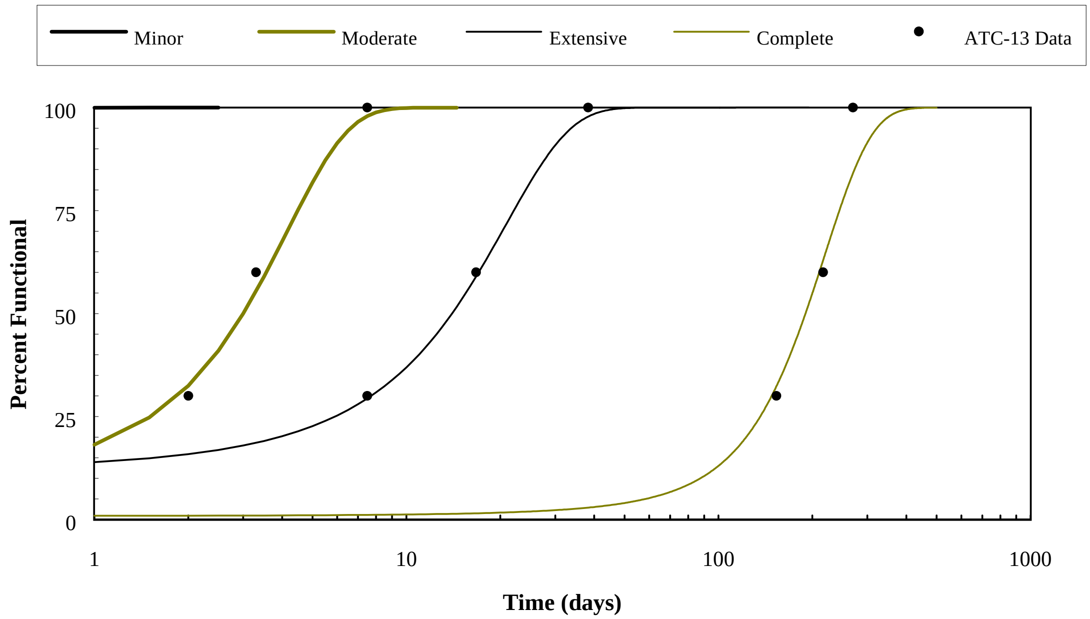


Figure 8.33: Restoration Curves for Tank Farms.

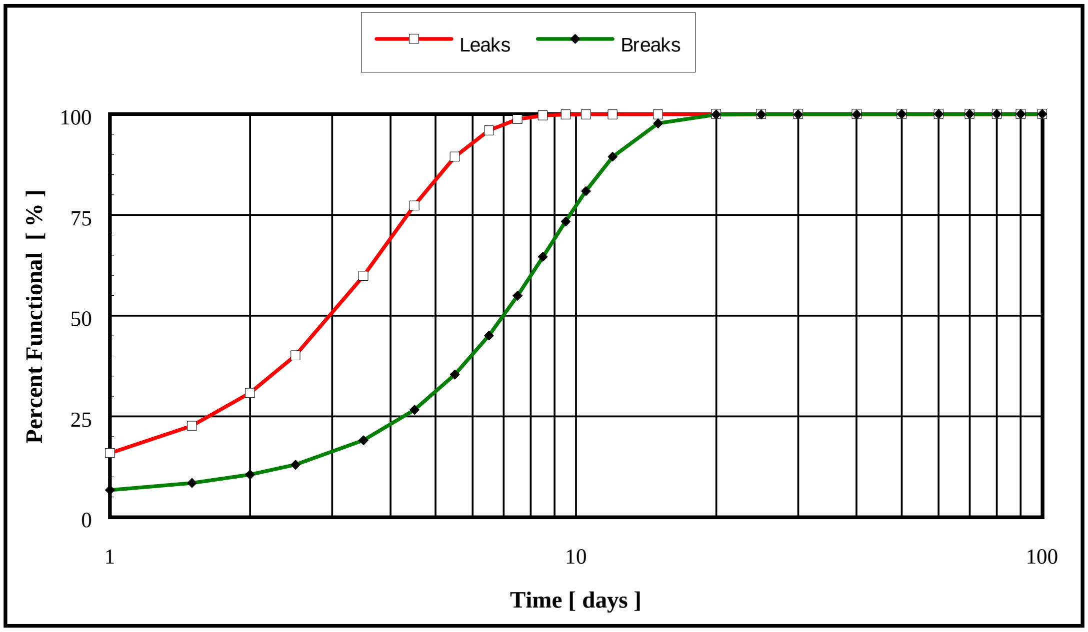


Figure 8.34: Restoration Curves for Oil Pipelines.

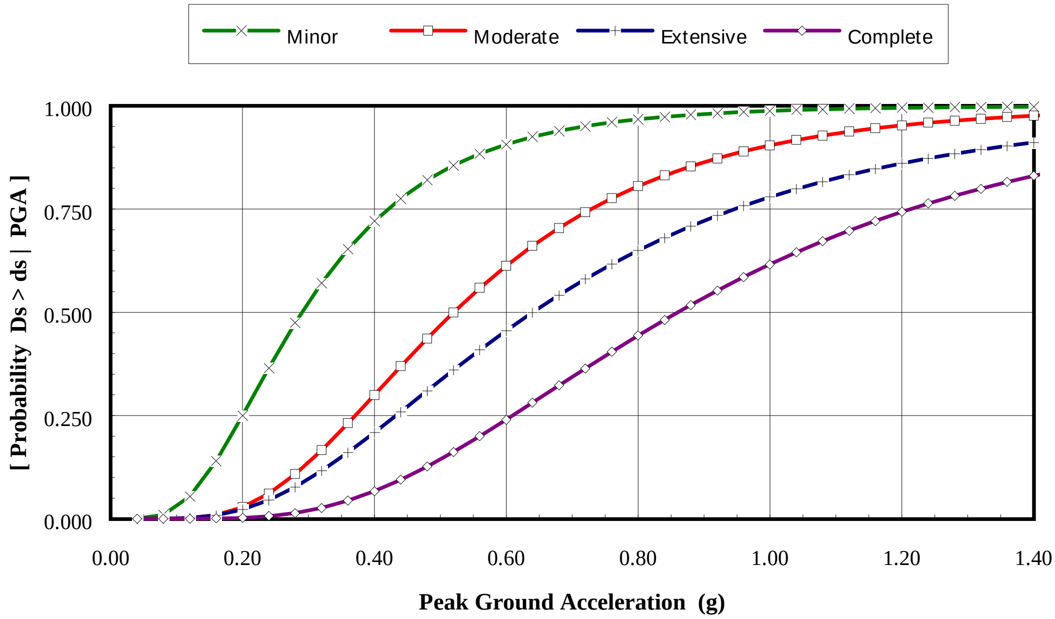


Figure 8.35: Fragility Curves for Small Refineries with Anchored Components.

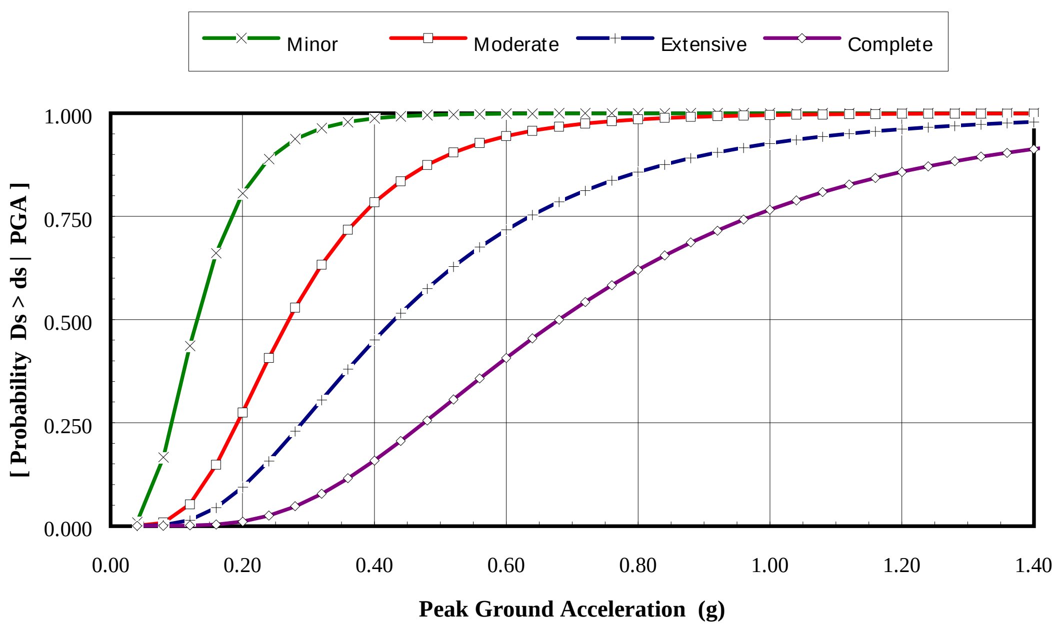


Figure 8.36: Fragility Curves for Small Refineries with Unanchored Components.

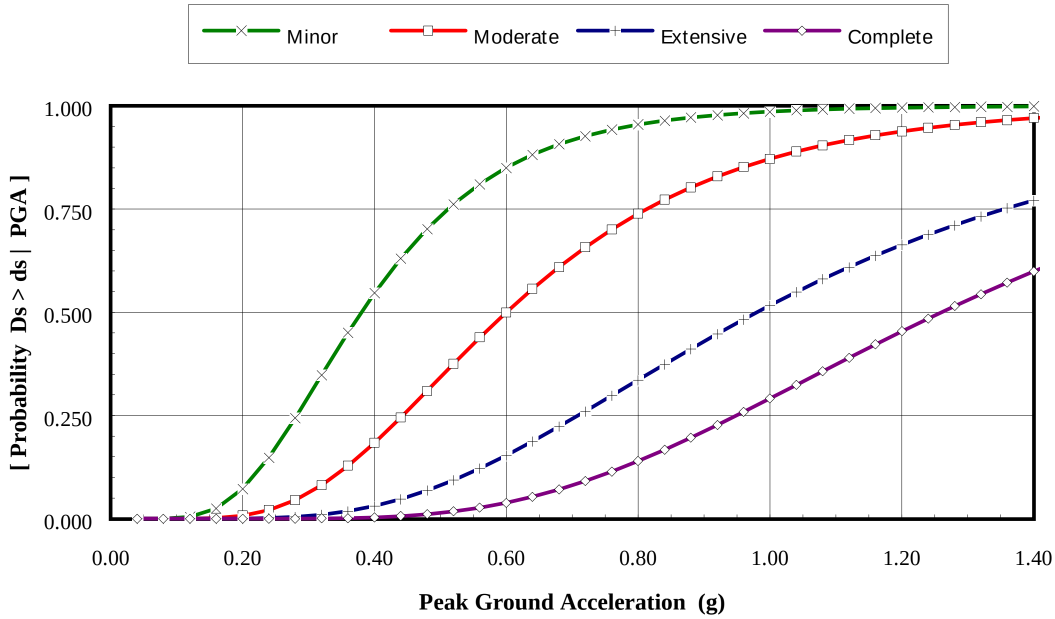


Figure 8.37: Fragility Curves for Medium/Large Refineries with Anchored Components.

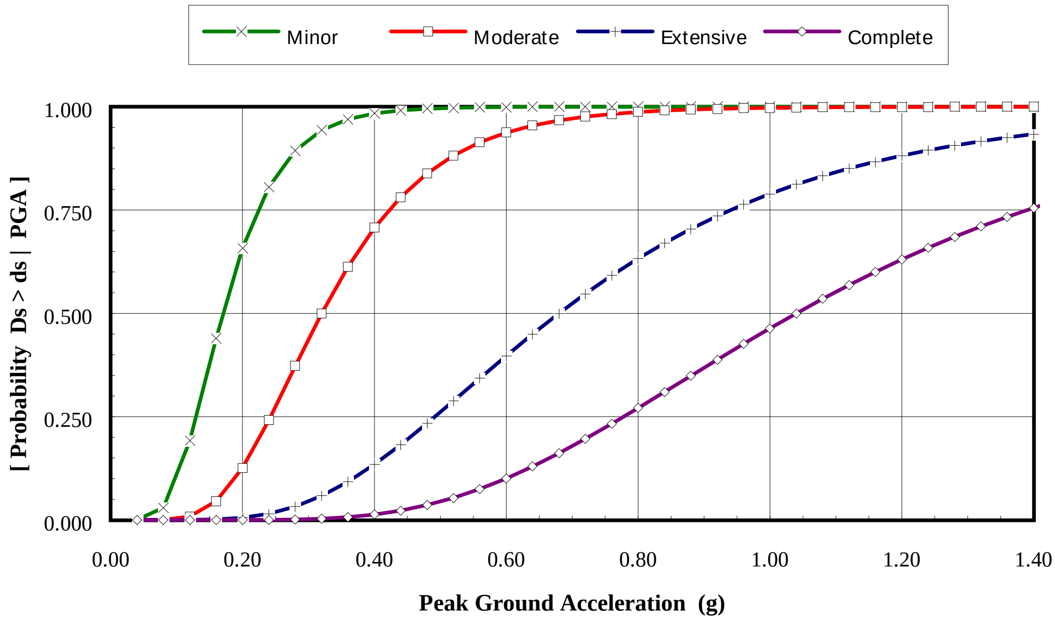


Figure 8.38: Fragility Curves for Medium/Large Refineries with Unanchored Components.

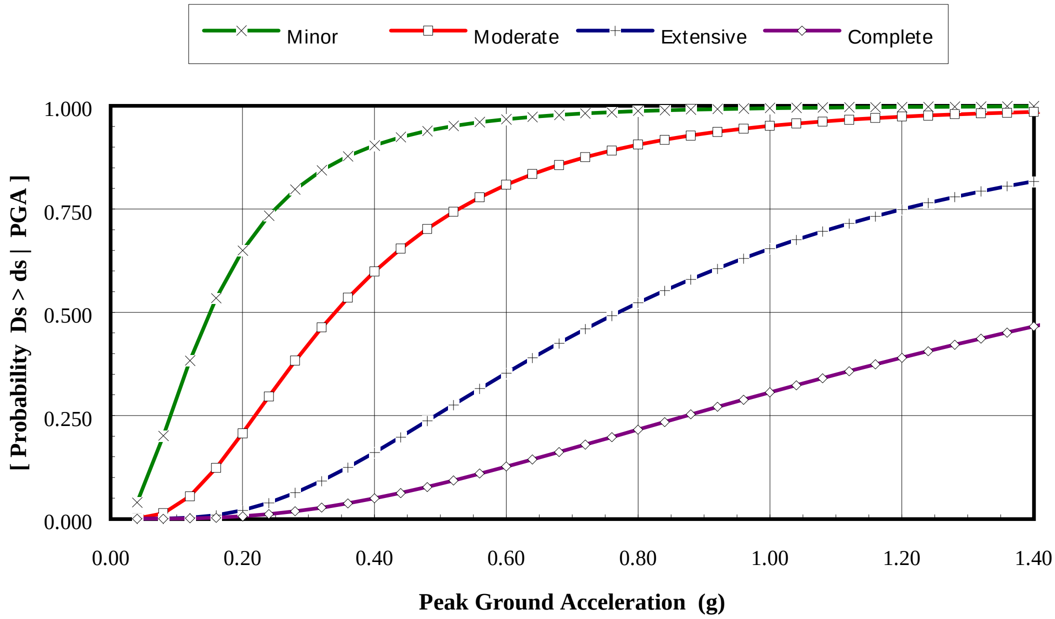


Figure 8.39: Fragility Curves for Pumping Plants with Anchored Components.

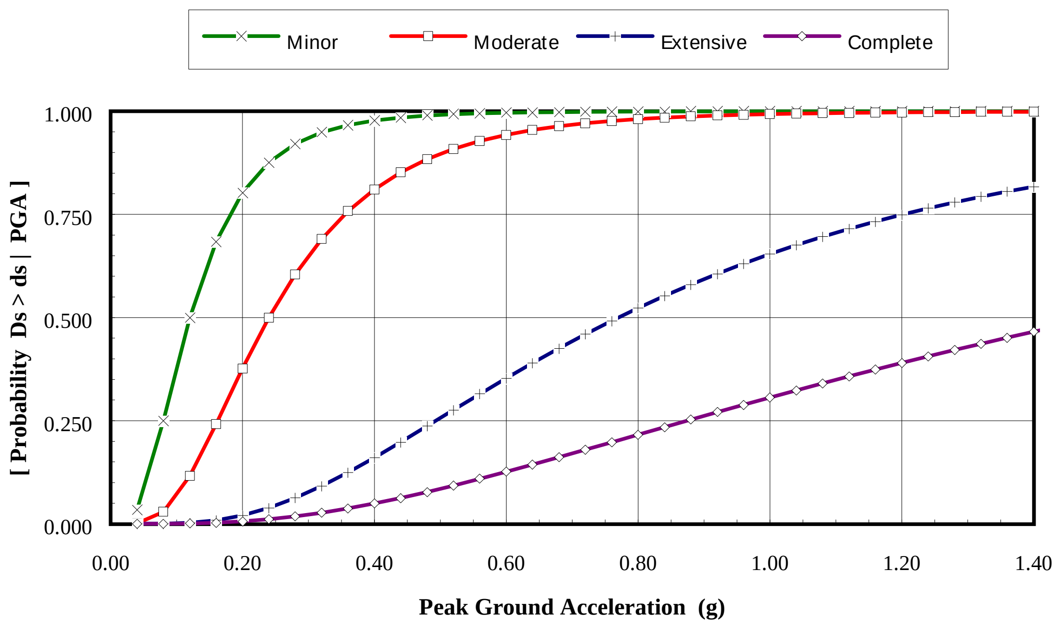


Figure 8.40: Fragility Curves for Pumping Plants with Unanchored Components.

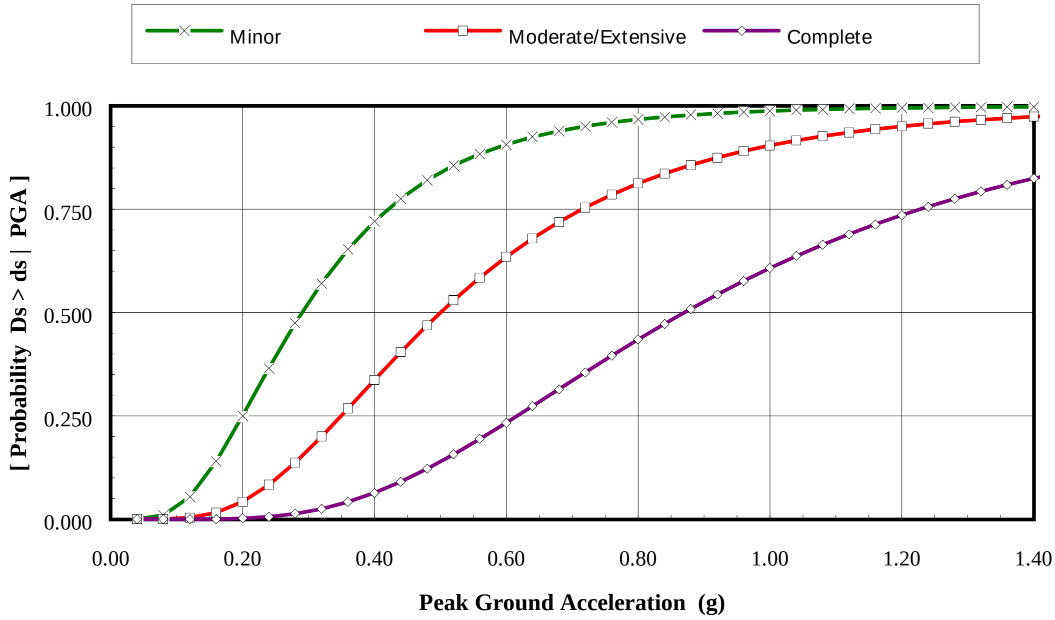


Figure 8.41: Fragility Curves for Tank Farms with Anchored Components.

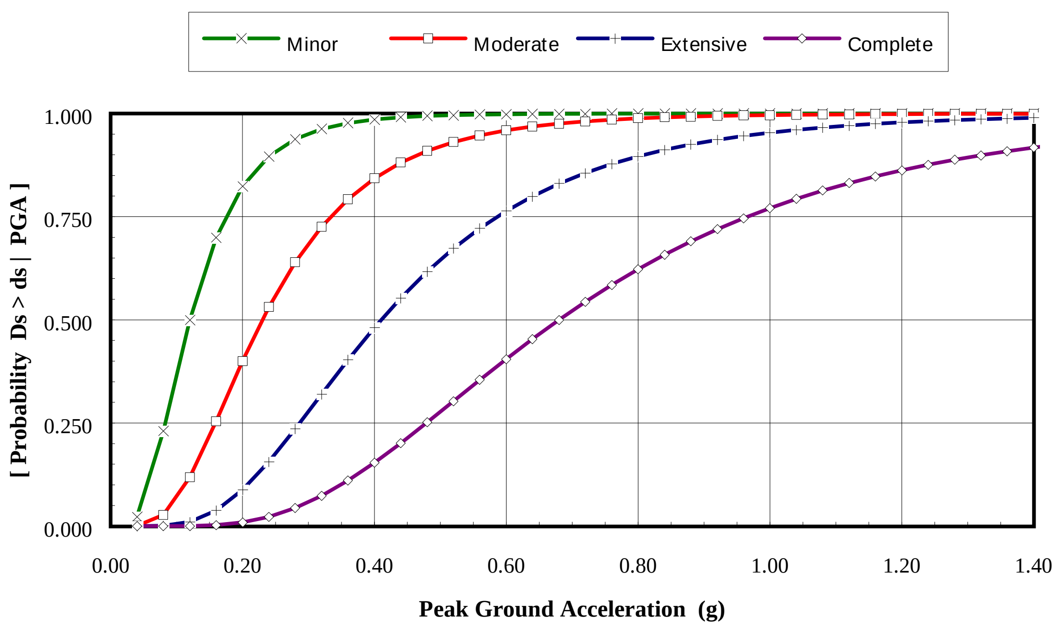


Figure 8.42: Fragility Curves for Tank Farms with Unanchored Components.

8.4 Natural Gas Systems

8.4.1 Introduction

A natural gas system consists of compressor stations and buried/elevated pipelines. Both of these components are vulnerable to damage during earthquakes. In addition to economic losses, failure of natural gas systems can also cause fires.

8.4.2 Scope

The scope of this section includes development of methods for estimation of earthquake damage to a natural gas system given knowledge of components (i.e. compressor stations), classification (i.e. for compressor stations, with anchored or unanchored components), and ground motion (i.e. peak ground velocity, peak ground acceleration and/or permanent ground deformation). Damage states describing the level of damage to each of the natural gas system components are defined (i.e., minor, moderate, extensive or complete for facilities and number of repairs/km for pipelines). Fragility curves are developed for each classification of the natural gas system component. These curves describe the probability of reaching or exceeding each damage state given the level of ground motion (or ground failure). Based on these fragility curves, functionality of each component of the natural gas system can be assessed.

8.4.3 Input Requirements and Output Information

Required input to estimate damage to natural gas systems are described below.

<u>Compressor Stations</u>

- Geographic location of facility (longitude and latitude)
- PGA and PGD
- Classification (w/ or w/o anchored components)

<u>Natural Gas Pipelines</u>

- Geographic location of pipeline links (longitude and latitude of end nodes)
- PGV and PGD
- Classification

Direct damage output for natural gas systems includes probability estimates of (1) component functionality and (2) damage, expressed in terms of the component's damage ratio (repair cost to replacement cost). Note that damage ratios for each of the natural gas system components are presented in section 15.3 of Chapter 15.

8.4.4 Form of Damage Functions

Damage functions or fragility curves for natural gas system components mentioned above are lognormally distributed functions that give the probability of reaching or exceeding different levels of damage for a given level of ground motion.

- For compressor stations, these fragility curves are defined by a median PGA/PGD and a dispersion.
- For natural gas pipelines, these fragility curves are defined by a median PGV/PGD and dispersion.

Definitions of various damage states and the methodology used in deriving all these fragility curves are presented in the next section.

8.4.5 Description of Natural Gas System Components

As mentioned before, a natural gas system typically consists of compressor stations and pipelines. In this section, a brief description of each of these components is given.

Compressor Stations

Compressor stations serve to maintain the flow of gas in cross-country pipelines. Compressor stations consist of either centrifugal or reciprocating compressors. However, no differentiation is made between these two types of compressors in the analysis of natural gas systems. Compressor stations are categorized as having either anchored or unanchored subcomponents, as defined in 7.2.5. The compressor stations are similar to pumping plants in oil systems discussed in Section 8.3.

Natural Gas Pipelines

Pipelines are typically made of mild steel with submerged arc welded joints, although older lines may have gas-welded joints. These are used for the transportation of natural gas over long distances. Many industries and residents could be severely affected should disruption of natural gas supplies occur.

8.4.6 Definitions of Damage States

Facilities such as compressor stations are mostly vulnerable to PGA, sometimes PGD, if located in liquefiable or landslide zones. Therefore, damage states for these components are defined and associated with either PGA or PGD. Pipelines, on the other hand, are vulnerable to PGV and PGD; therefore, damage states for these components are associated with these two ground motion parameters.

8.4.6.1 Damage States Definitions for Compressor Stations

A total of five damage states are defined for gas system components. These are none (ds_1), slight/minor (ds_2), moderate (ds_3), extensive (ds_4) and complete (ds_5).

Slight/Minor Damage (ds_2)

- ds_2 is defined by slight damage to building.

Moderate Damage (ds_3)

- ds_3 is defined by considerable damage to mechanical and electrical equipment, or considerable damage to building.

Extensive Damage (ds_4)

- ds_4 is defined by the building being extensively damaged, or the pumps badly damaged beyond repair.

Complete Damage (ds_5)

- ds_5 is defined by the building in complete damage state.

8.4.6.2 Damage States Defintions for Pipelines

For pipelines, two damage states are considered. These are leaks and breaks. Generally, when a pipe is damaged due to ground failure, the type of damage is likely to be a break, while when a pipe is damaged due to seismic wave propagation; the type of damage is likely to be local bucking of the pipe wall. In the loss methodology, it is assumed that damage due to seismic waves will consist of 80% leaks and 20% breaks, while damage due to ground failure will consist of 20% leaks and 80% breaks. The user can override these default percentages.

8.4.7 Component Restoration Curves

The restoration curves for natural gas system components are similar to those of the oil system discussed in Section 8.3.7. Compressor stations in natural gas systems are analogous to pumping plants in oil systems.

8.4.8 Development of Damage Functions

Fragility curves for natural gas system components are defined with respect to classification and ground motion parameter.

<u>Damage Functions for Compressor Stations</u>

Damage functions for compressor stations are taken as identical to those of pumping plants in oil systems discussed in Section 8.3.8.

<u>Damage Functions for Pipelines</u>

Damage functions for natural gas pipelines are taken as identical to those for oil pipelines discussed in Section 8.3.8.

8.4.9 Guidance for Loss Estimation with Advanced Data and Models Analysis

For this type of analysis, the expert can use the methodology developed with the flexibility to (1) include a more refined inventory of the natural gas system pertaining to the area of study, and (2) include component-specific and system-specific fragility data. Default damage algorithms for User-Supplied Data Analysis can be modified or replaced to incorporate improved information about key components of a natural system. Similarly, better restoration curves can be developed, given knowledge of available resources.

8.4.10 References

(1) ATC-13, "Earthquake Damage Evaluation Data for California", Applied Technology Council, Redwood City, CA, 1985.

(2) G&E Engineering Systems, Inc. (G&E), "NIBS Earthquake Loss Estimation Methods, Technical Manual, (Fuel Systems)", June 1994.

8.5 Electric Power Systems

8.5.1 Introduction

This section presents the earthquake loss estimation methodology for an electric power system. This system consists of generation facilities, substations, and distribution circuits. All of these components are vulnerable to damage during earthquakes, which may result in significant disruption of power supply.

8.5.2 Scope

The scope of this section includes development of methods for estimating earthquake damage to an electric power system given knowledge of components (i.e. generation facilities, substations, and distribution circuits), classification (i.e., for substations, low voltage, medium voltage, or high voltage), and the ground motion (i.e. peak ground acceleration and permanent ground deformation). Damage states describing the level of damage to each of the electric power system components are defined (i.e., minor, moderate, extensive or complete). Fragility curves are developed for each classification of the electric power system component. These curves describe the probability of reaching or exceeding each damage state given the level of ground motion.

Based on these fragility curves, the method for assessing functionality of each component of the electric power system is presented.

8.5.3 Input Requirements and Output Information

Required input to estimate damage to electric power systems includes the following items:

Substations

- Longitude and latitude of facility
- PGA and PGD
- Classification (low, medium, or high voltage; with anchored or standard components)

Distribution Circuits

- Longitude and latitude of facility
- PGA
- Classification (seismically designed or standard components)

Generation Plants

- Longitude and latitude of facility
- PGA
- Classification (small or medium/large, with anchored or unanchored components)

Direct damage output for an electric power system includes probability estimates of (1) component functionality and (2) damage, expressed in terms of the component's damage ratio. Damage ratios for electric power systems components are presented in section 15.3 of Chapter 15. A simplified system performance evaluation methodology is also provided. The output from this simplified version of system analysis consists of a probabilistic estimate for the power outage.

8.5.4 Form of Damage Functions

Damage functions or fragility curves for all electric power system components mentioned above are modeled as lognormally-distributed functions that give the probability of reaching or exceeding different levels of damage for a given level of ground motion. These fragility curves are defined by a median ground motion parameter and a dispersion.

8.5.5 Description of Electric Power System Components

As mentioned before, the components of an electric power system considered in the loss estimation methodology are substations, distribution circuits, and generation plants. In this section a brief description of each of these components is presented.

Substations

An electric substation is a facility that serves as a source of energy supply for the local distribution area in which it is located, and has the following main functions:

- Change or switch voltage from one level to another.
- Provide points where safety devices such as disconnect switches, circuit breakers, and other equipment can be installed.
- Regulate voltage to compensate for system voltage changes.
- Eliminate lightnning and switching surges from the system.
- Convert AC to DC and DC to AC, as needed.
- Change frequency, as needed.

Substations can be entirely enclosed in buildings where all the equipment is assembled into one metal clad unit. Other substations have step-down transformers, high voltage switches, oil circuit breakers, and lightning arrestors located outside the substation building. In the current loss estimation methodology, only transmission (138 kV to 765 kV or higher) and subtransmission (34.5 kV to 161 kV) substations are considered. These will be classified as high voltage (350 kV and above), medium voltage (150 kV to 350 kV) and low voltage (34.5 kV to 150 kV), and will be referred to as 500 kV substations, 230kV substations, and 115kV substations, respectively. The classification is also a function of whether the subcomponents are anchored or typical (unanchored), as defined in 7.2.5.

Distribution Circuits

The distribution system is divided into a number of circuits. A distribution circuit includes poles, wires, in-line equipment and utility-owned equipment at customer sites. A distribution circuit also includes above ground and underground conductors. Distribution circuits either consist of anchored or unanchored components.

Generation Plants

These plants produce alternating current (AC) and may be any of the following types:

- Hydroelectric
- Steam turbine (fossil fuel fired or nuclear)
- Combustion turbine (fossil fuel fired)
- Geothermal
- Solar
- Wind
- Compressed air

Fossil fuels are either coal, oil, or natural gas.
Generation plant subcomponents include diesel generators, turbines, racks and panels, boilers and pressure vessels, and the building in which these are housed.

The size of the generation plant is determined from the number of Megawatts of electric power that the plant can produce under normal operations. Small generation plants have a generation capacity of less than 200 Megawatts. Medium/Large generation plants have a capacity greater than 200 Megawatts. Fragility curves for generation plants with anchored versus unanchored subcomponents are presented.

8.5.6 Definitions of Damage States

Electric power systems are susceptible to earthquake damage. Facilities such as substations, generation plants, and distribution circuits are mostly vulnerable to PGA, and sometimes PGD, if located in liquefiable or landslide zones. Therefore, the damage states for these components are defined in terms of PGA and PGD.

A total of five damage states are defined for electric power system components. These are none (ds_1), slight/minor (ds_2), moderate (ds_3), extensive (ds_4) and complete (ds_5).

Note that for power systems, in particular for substations and distribution circuits, these damage states are defined with respect to the percentage of subcomponents being damaged. That is, for a substation with n_1 transformers, n_2 disconnect switches, n_3 circuit breakers, and n_4 current transformers, the substation is said to be in a slight or minor damage state if 5% of n_2 or 5% of n_3 are damaged, and it is in the extensive damage state if 70% of n_1, 70% of n_2, or 70% of n_3 are damaged, or if the building is in extensive damage state. A parametric study on n_1, n_2, n_3, and n_4 values shows that the medians of the damage states defined in this manner don't change appreciably (less than 3 %) as the n_i's vary, while the corresponding dispersions get smaller as the n_i's increase. Therefore, we used dispersions obtained from the small sample numbers along with the relatively constant median values.

Slight/Minor Damage (ds_2)

- For substations, ds_2 is defined as the failure of 5% of the disconnect switches (i.e., misalignment), or the failure of 5 % of the circuit breakers (i.e., circuit breaker phase sliding off its pad, circuit breaker tipping over, or interrupter-head falling to the ground), or by the building being in minor damage state.

- For distribution circuits, ds_2 is defined by the failure of 4 % of all circuits.

- For generation plants, ds_2 is defined by turbine tripping, or light damage to diesel generator, or by the building being in minor damage state.

Moderate Damage (ds_3)

- For substations, ds_3 is defined as the failure of 40% of disconnect switches (e.g., misalignment), or 40% of circuit breakers (e.g., circuit breaker phase sliding off its pad, circuit breaker tipping over, or interrupter-head falling to the ground), or failure of 40% of current transformers (e.g., oil leaking from transformers, porcelain cracked), or by the building being in moderate damage state.

- For distribution circuits, ds_3 is defined by the failure of 12% of circuits.

- For generation plants, ds_3 is defined some by the chattering of instrument panels and racks, considerable damage to boilers and pressure vessels, or by the building being in moderate damage state.

Extensive Damage (ds_4)

- For substations, ds_4 is defined as the failure of 70% of disconnect switches (e.g., misalignment), 70% of circuit breakers, 70% of current transformers (e.g., oil leaking from transformers, porcelain cracked), or by failure of 70% of transformers (e.g., leakage of transformer radiators), or by the building being in extensive damage state.

- For distribution circuits, ds_4 is defined by the failure of 50% of all circuits.

- For generation plants, ds_4 is defined by considerable damage to motor driven pumps, or considerable damage to large vertical pumps, or by the building being in extensive damage state.

Complete Damage (ds_5)

- For substations, ds_5 is defined as the failure of all disconnect switches, all circuit breakers, all transformers, or all current transformers, or by the building being in complete damage state.
- For distribution circuits, ds_5 is defined by the failure of 80% of all circuits.
- For generation plants, ds_5 is defined by extensive damage to large horizontal vessels beyond repair, extensive damage to large motor operated valves, or by the building being in complete damage state.

8.5.7 Component Restoration Curves

Restoration curves for electric substations and distribution circuits are based on a G&E report (1994), while restoration curves for generation facilities are obtained using the data for mean restoration times from ATC-13 social function SF-29.a (the first four damage states). These functions are presented in Tables 8.22.a and 8.22.b. The first table gives means and standard deviations for each restoration curve (i.e., smooth continuous curve), while the second table gives approximate discrete functions for the restoration curves developed. These restoration functions are also shown in Figures 8.43 through 8.45.

Table 8.22.a: Restoration Functions for Electric Power System Components

Restoration Functions (All Normal Distributions)			
Classification	**Damage State**	**Mean (Days)**	**β**
Electric Sub-Stations	slight/minor	1.0	0.5
	moderate	3.0	1.5
	extensive	7.0	3.5
	complete	30.0	15.0
Distribution Circuits	slight/minor	0.3	0.2
	moderate	1.0	0.5
	extensive	3.0	1.5
	complete	7.0	3.0
Generation Facilities	slight/minor	0.5	0.1
	moderate	3.6	3.6
	extensive	22.0	21.0
	complete	65.0	30.0

Table 8.22.b: Discretized Restoration Functions for Electric Power Components

Discretized Restoration Functions						
Classification	**Damage State**	**1 day**	**3 days**	**7 days**	**30 days**	**90 days**
Electric Sub-Stations	slight/minor	50	100	100	100	100
	moderate	9	50	100	100	100
	extensive	4	13	50	100	100
	complete	3	4	7	50	100
Distribution Circuits	slight/minor	100	100	100	100	100
	moderate	50	100	100	100	100
	extensive	9	50	100	100	100
	complete	2	10	50	100	100
Generation Facilities	slight/minor	100	100	100	100	100
	moderate	24	44	83	100	100
	extensive	16	19	24	65	100
	complete	2	2	3	13	80

8.5.8 Development of Damage Functions

Fragility curves for electric power system components are defined with respect to classification and ground motion parameters. These curves are based on the probabilistic combination of subcomponent damage functions using Boolean expressions to describe the relationship of subcomponents. The Boolean approach involves evaluation of the probability of each component reaching or exceeding different damage states, as defined by the damage level of its subcomponents. It should be mentioned that the Boolean logic is implicitly presented within the definition of a particular damage state. For example, the moderate damage state for substations is defined as the failure of 40% of disconnect switches, <u>OR</u> the failure of 40% of circuit breakers, <u>OR</u> the failure of 40% of transformers, <u>OR</u> by the building being in moderate damage state. Therefore, the fault tree for moderate damage for substations has <u>FOUR</u> primary <u>OR</u> branches: disconnect switches, circuit breakers, transformers, and building. Within the first 3 <u>OR</u> branches (i.e., disconnect switches, circuit breakers, and transformers) the multiple possible combinations are considered. These evaluations produce component probabilities at various levels of ground motion. In general, the Boolean combinations do not produce a lognormal distribution, so a lognormal curve that best fits this probability distribution is determined numerically.

Damage functions due to ground failure (i.e., PGD) for substations and generation plants are assumed to be similar to those described for potable water system facilities in section 8.1.8.

<u>PGA Related Damage Functions for Electric Power Substations</u>

A total of 24 sub-station damage functions are used in the methodology. Half of these damage functions correspond to substations with anchored components, while the other half correspond to substations with unanchored components. Medians and dispersions of these damage functions are given in Tables 8.23 and

8.24. These damage functions are also presented in the form of fragility curves in Figures 8.46 through 8.51. Note that each figure contains four damage functions.

Table 8.23: Damage Algorithms for Substations (Anchored / Seismic Components)

Peak Ground Acceleration			
Classification	**Damage State**	**Median (g)**	**β**
Low voltage (ESS1)	slight/minor	0.15	0.70
	moderate	0.29	0.55
	extensive	0.45	0.45
	complete	0.90	0.45
Medium voltage (ESS3)	slight/minor	0.15	0.60
	moderate	0.25	0.50
	extensive	0.35	0.40
	complete	0.70	0.40
High voltage (ESS5)	slight/minor	0.11	0.50
	moderate	0.15	0.45
	extensive	0.20	0.35
	complete	0.47	0.40

Table 8.24: Damage Algorithms for Substations (Unanchored / Standard Components)

Peak Ground Acceleration			
Classification	**Damage State**	**Median (g)**	**β**
Low voltage (ESS2)	slight/minor	0.13	0.65
	moderate	0.26	0.50
	extensive	0.34	0.40
	complete	0.74	0.40
Medium voltage (ESS4)	slight/minor	0.10	0.60
	moderate	0.20	0.50
	extensive	0.30	0.40
	complete	0.50	0.40
High voltage (ESS6)	slight/minor	0.09	0.50
	moderate	0.13	0.40
	extensive	0.17	0.35
	complete	0.38	0.35

PGA Related Damage Functions for Distribution Circuits

A total of 8 distribution circuits damage functions are obtained. Four of these damage functions correspond to distribution circuits with seismically designed components, while the other four correspond to distribution circuits with standard components. Medians and dispersions of these damage functions are presented in Table 8.25 and plotted in Figures 8.52 and 8.53. Note that subcomponent damage functions of a distribution circuit are presented in Table D.8.7 of Appendix 8D.

Table 8.25: Damage Algorithms for Distribution Circuits

Peak Ground Acceleration			
Classification	**Damage State**	**Median (g)**	**β**
Seismic Components (EDC1)	slight/minor	0.28	0.30
	moderate	0.40	0.20
	extensive	0.72	0.15
	complete	1.10	0.15
Standard Components (EDC2)	slight/minor	0.24	0.25
	moderate	0.33	0.20
	extensive	0.58	0.15
	complete	0.89	0.15

PGA Related Damage Functions for Generation Plants

A total of 16 damage functions for generation plants are developed. Eight of these damage functions correspond to small generation plants (less than 200 MW), while the other eight correspond to medium/large plants (more than 200 MW). Medians and dispersions of these damage functions are given in Tables 8.26 and 8.27. These damage functions are also shown as fragility curves in Figures 8.54 through 8.57. Note that subcomponent damage functions of a generation plant are presented in Tables D.8.8 and D.8.9 of Appendix 8D.

Table 8.26: Damage Algorithms for Small Generation Facilities

Peak Ground Acceleration			
Classification	**Damage State**	**Median (g)**	**β**
Facility with Anchored Components (EPP1)	slight/minor	0.10	0.55
	moderate	0.21	0.55
	extensive	0.48	0.50
	complete	0.78	0.50
Facility with Unanchored Components (EPP2)	slight/minor	0.10	0.50
	moderate	0.17	0.50
	extensive	0.42	0.50
	complete	0.58	0.55

Table 8.27: Damage Algorithms for Medium/Large Generation Facilities

Peak Ground Acceleration			
Classification	**Damage State**	**Median (g)**	**β**
Facility with Anchored Components (EPP3)	slight/minor	0.10	0.60
	moderate	0.25	0.60
	extensive	0.52	0.55
	complete	0.92	0.55
Facility with Unanchored Components (EPP4)	slight/minor	0.10	0.60
	moderate	0.22	0.55
	extensive	0.49	0.50
	complete	0.79	0.50

8.5.9 Power Outage and Performance Evaluation for Electric Power Systems

For electric power systems, power service outages for the study region are assumed to be dependent on the nonfunctionality of substations servicing the region. This component is in fact among one of the more vulnerable electric power component to earthquake, and damage to this facility affects wide areas.

Example

Assume that in a study region, in the Western US, there are 2 medium voltage substations, both with anchored designed components. At one facility the PGA is 0.15g while at the other facility the PGA is 0.3g. We want to evaluate the electric power system performance. The damage and restoration algorithms for medium voltage substations are reproduced in Table 8.28.

Table 8.28: Electric Power System Performance Example Parameters

Medium Voltage Substations with Seismic Components				
Damage State	**Median (g)**	**β**		
slight/minor	0.15	0.6		
moderate	0.25	0.5		
extensive	0.35	0.4		
complete	0.7	0.4		
Continuous Restoration Functions (All Normal Distributions)				
Damage State	**Mean (days)**	**σ (days)**		
slight/minor	1.0	0.5		
moderate	3.0	1.5		
extensive	7.0	3.5		
complete	30	15		
Discretized Restoration Functions				
Damage State	**3 days**	**7 days**	**30 days**	**90 days**
slight/minor	100	100	100	100
moderate	50	100	100	100
extensive	13	50	100	100
complete	4	7	50	100

The discrete probabilities for different damage states are then determined at these two substations:

At Substation 1,

$$P[\,D_S = ds_1 \mid PGA = 0.15g\,] = 0.50$$
$$P[\,D_S = ds_2 \mid PGA = 0.15g\,] = 0.35$$
$$P[\,D_S = ds_3 \mid PGA = 0.15g\,] = 0.13$$
$$P[\,D_S = ds_4 \mid PGA = 0.15g\,] = 0.02$$
$$P[\,D_S = ds_5 \mid PGA = 0.15g\,] = 0.00$$

At substation 2,

$$P[\,D_S = ds_1 \mid PGA = 0.3g\,] = 0.12$$
$$P[\,D_S = ds_2 \mid PGA = 0.3g\,] = 0.24$$
$$P[\,D_S = ds_3 \mid PGA = 0.3g\,] = 0.29$$
$$P[\,D_S = ds_4 \mid PGA = 0.3g\,] = 0.33$$
$$P[\,D_S = ds_5 \mid PGA = 0.3g\,] = 0.02$$

The best estimate of functionality for each restoration period is estimated by the weighted combination:

$$FP_C = \sum_{i=1}^{i=5} FR_i \times P[ds_i]$$

In this example, the weighted combination after 3 days would be:

At substation # 1,
FP_C [3 days] = 0.5 x 100% + 0.35 x 100% + 0.13 x 50% + 0.02 x 13% + 0.0 x 4%
= 91.8 %

At substation # 2,
FP_C [3 days] = 0.12 x 100 %+ 0.24 x 100% + 0.29 x 50% + 0.33 x 13% + 0.02 x 4%
= 54.9 %

Therefore, in the study region and 3 days after the earthquake, about 8% of the area serviced by substation # 1 will be still suffering power outage while 45% of the area serviced by substation # 2 will be still out of power, or in average 23% of the whole study region will be out of power.

Note that the expected number of customers without power after each restoration period is estimated by multiplying the probability of power outage with the number of households (housing units) in each census tract.

Finally, it should be mentioned that the interaction between electric power and other lifeline systems was considered marginally through a fault tree analysis. Loss of electric power is assumed to affect only the slight/minor and moderate damage states of other lifeline systems that depend on power. This assumption is based on the fact that if a water treatment plant, for example, is in the extensive damage state that the availability of power becomes of secondary importance. The fault tree analysis also assumes that the substation serving the other lifeline components it interacts with will be subject to a comparable level of ground motion. The following generic electric power damage functions (based largely on medium voltage substations damage functions) are considered for lifeline interaction:

Table 8.29: Generic Damage Algorithm for Electric Power System

Peak Ground Acceleration			
Subcomponents	**Damage State**	**Median (g)**	**β**
Loss of Commercial Power	slight/minor moderate	0.15 0.30	0.40 0.40

8.5.10 Guidance for Loss Estimation with Advanced Data and Models Analysis

For this type of analysis, the expert can use the methodology developed for User-Supplied Data Analysis with the flexibility to (1) include a refined inventory of the electric power system pertaining to the area of study, and (2) include component-specific and system-specific fragility data, and (3) perform a network analysis of actual circuits to better estimate the overall system functionality. Default damage algorithms for User-Supplied Data Analysis can be modified or replaced to accommodate any specified key component of an electric power system. Similarly, better restoration curves could be developed given knowledge of available resources and a more accurate layout of the network within the local topographic and geological conditions.

8.5.11 References

(1) ATC-13, "Earthquake Damage Evaluation Data for California", Applied Technology Council, Redwood City, CA, 1985.

(2) G&E Engineering Systems, Inc. (G&E), "NIBS Earthquake Loss Estimation Methods, Technical Manual, (Electric Power Systems)", June 1994.

(3) Schiff A., "Seismic Design Practices for Power Systems: Evolution, Evaluation, and Needs", TCLEE Monograph No. 4 August, 1991.

(4) Matsuda et al., "Earthquake Evaluation of a Substation Network", TCLEE Monograph No. 4 August, 1991.

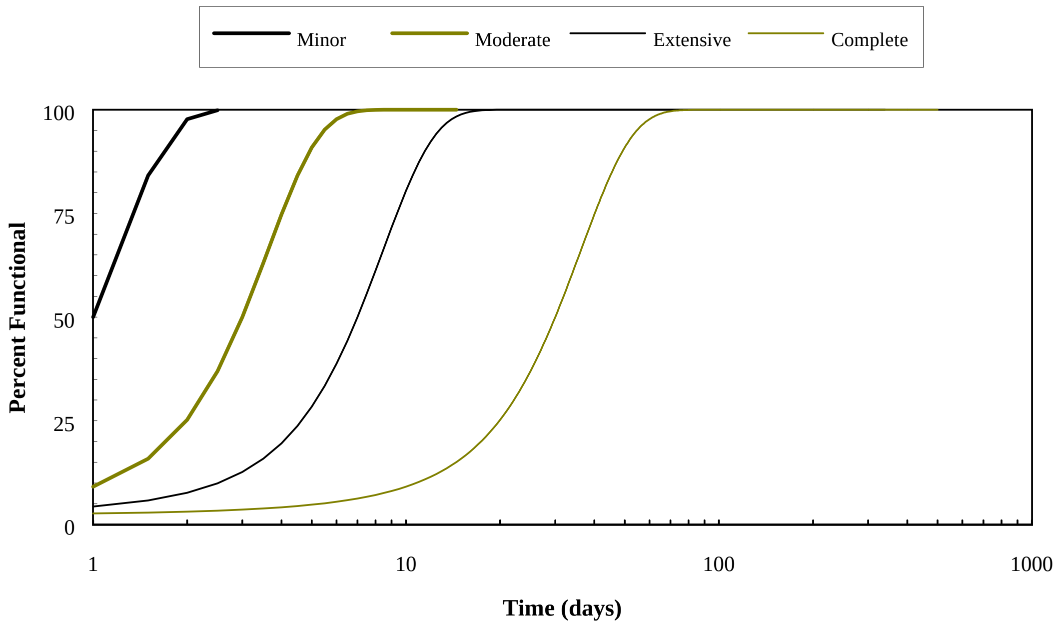


Figure 8.43: Restoration Curves for Electric Substations.

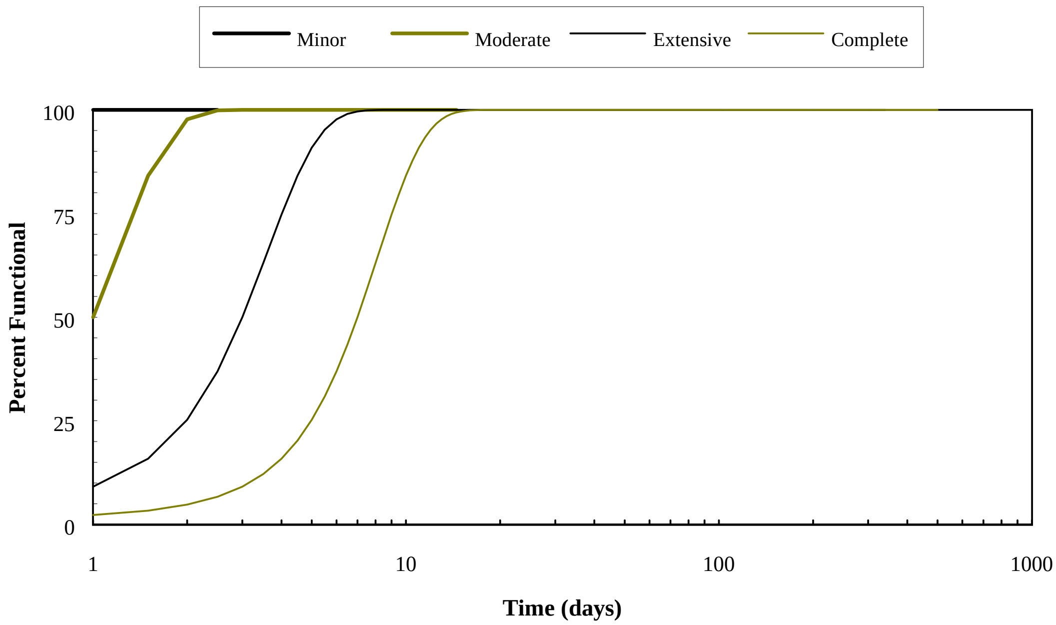


Figure 8.44: Restoration Curves for Distribution Circuits.

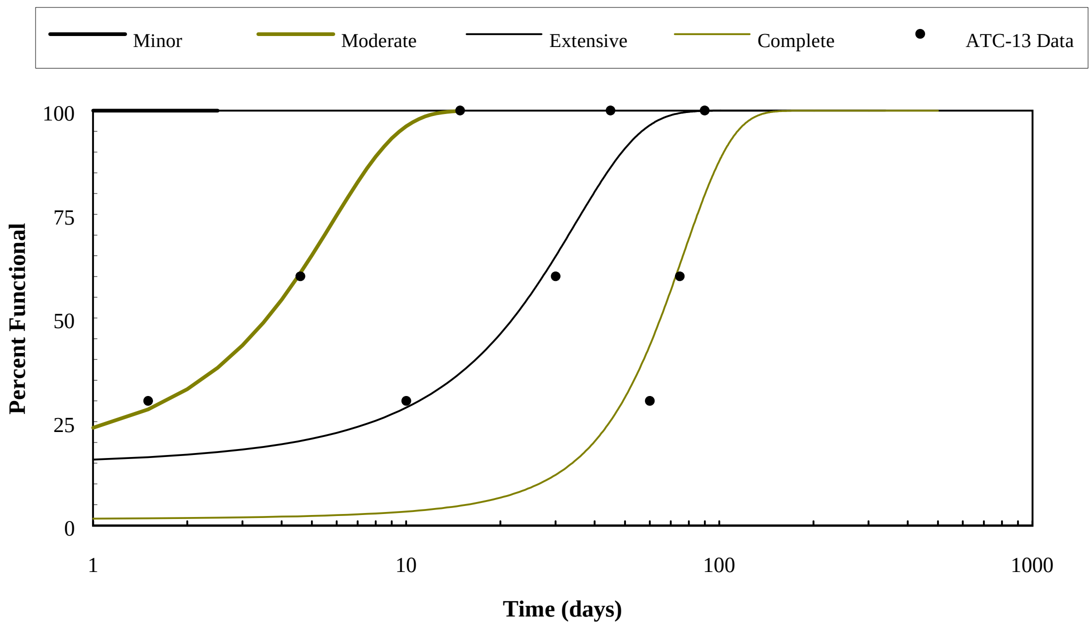


Figure 8.45: Restoration Curves for Generation Facilities.

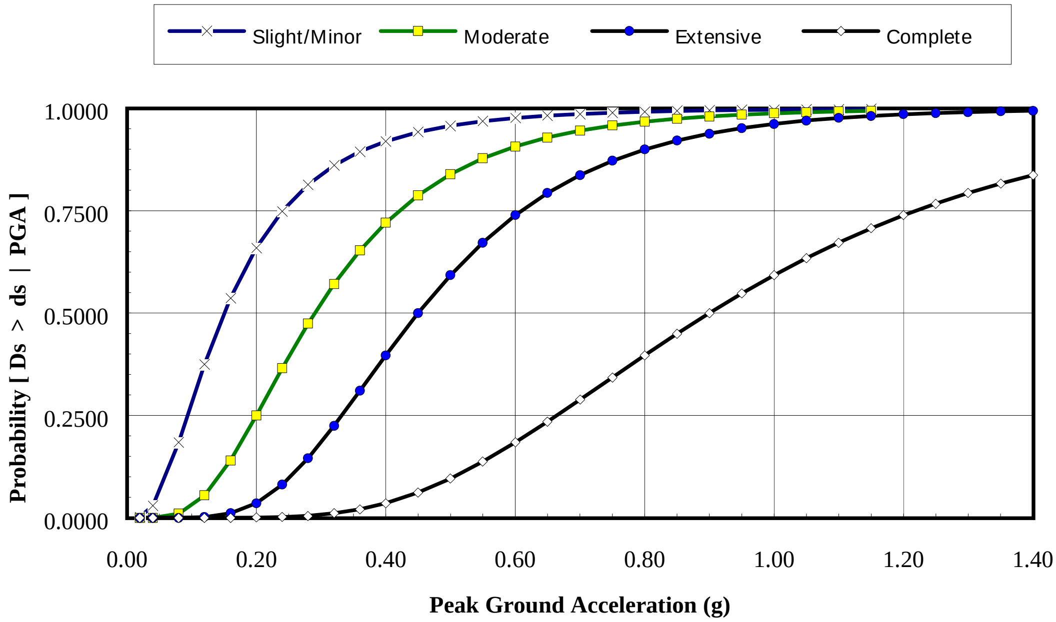


Figure 8.46: Fragility Curves for Low voltage Substations with Seismic Components.

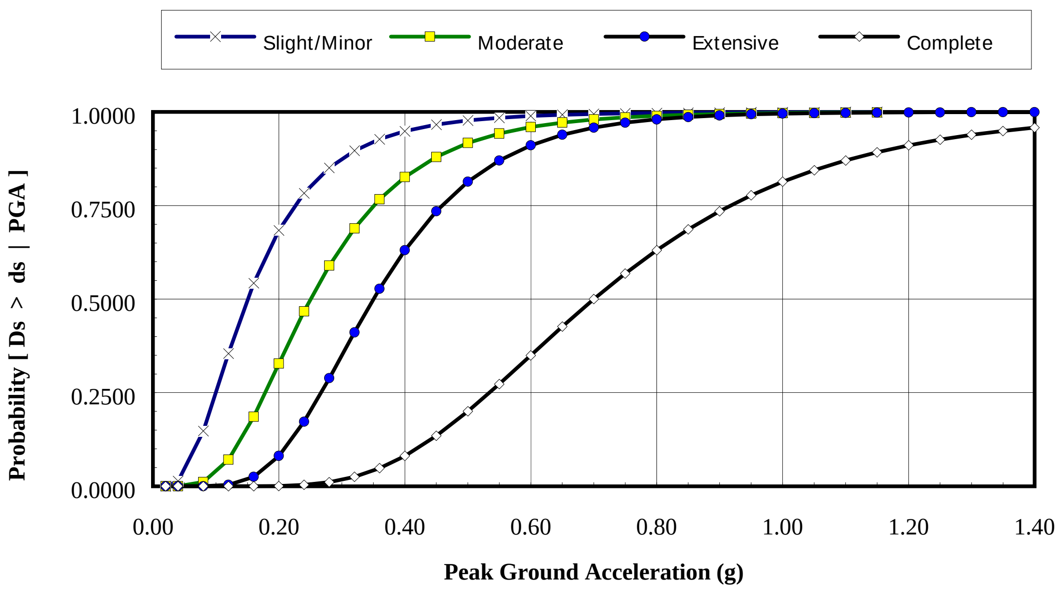


Figure 8.47: Fragility Curves for Medium Voltage Substations with Seismic Components.

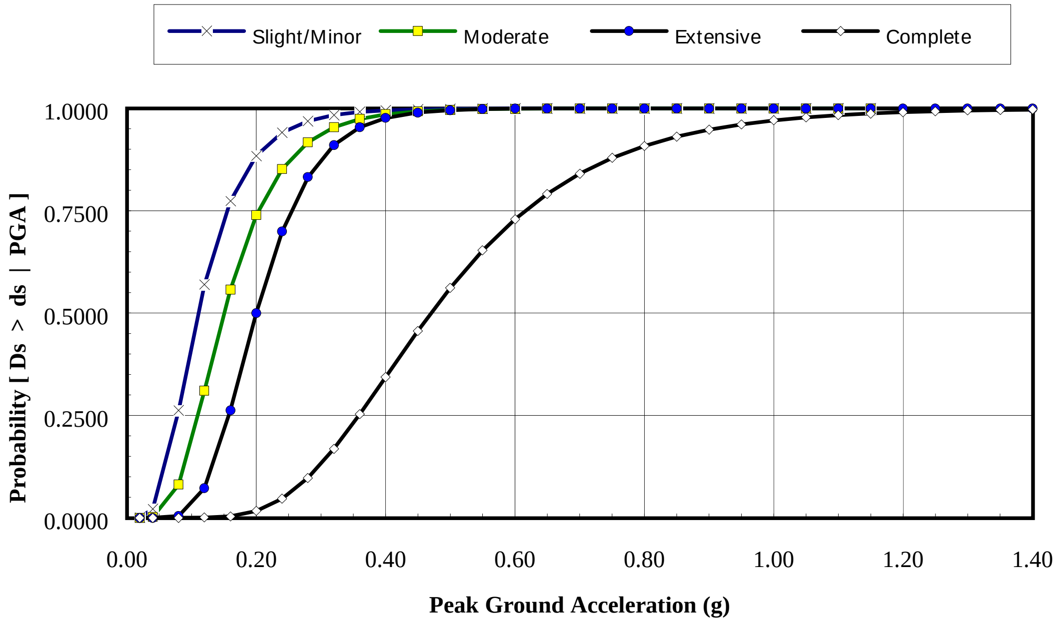


Figure 8.48: Fragility Curves for High Voltage Substations with Seismic Components.

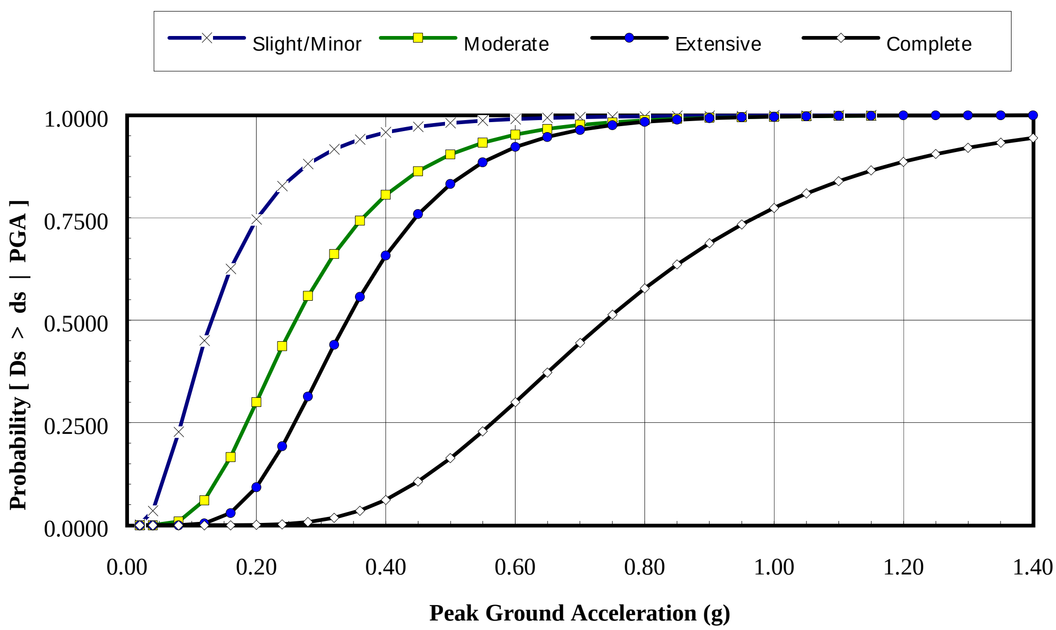


Figure 8.49: Fragility Curves for Low Voltage Substations with Standard Components.

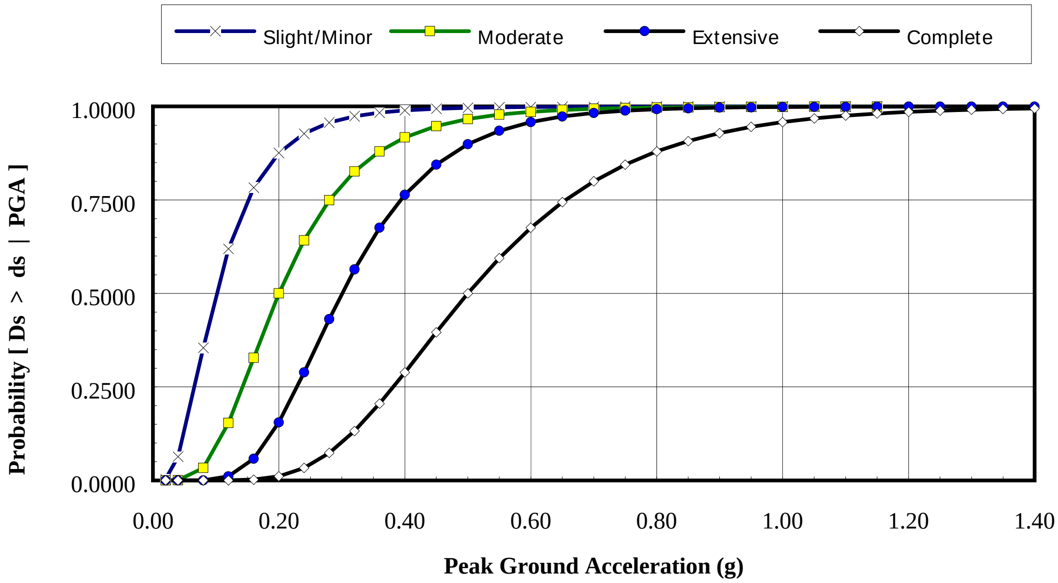


Figure 8.50: Fragility Curves for Medium Voltage Substations with Standard Components.

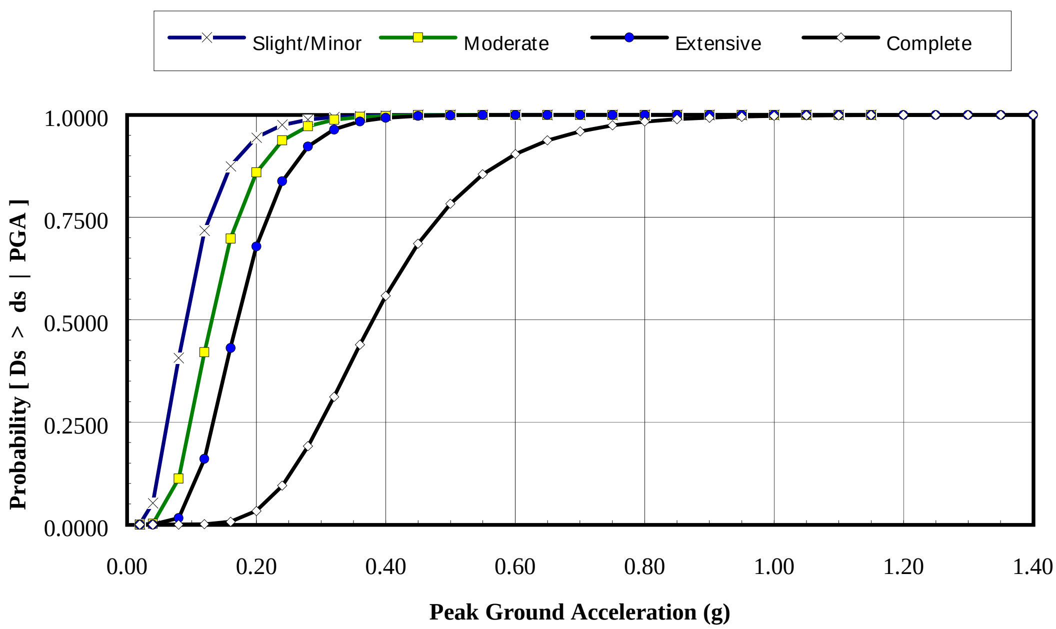


Figure 8.51: Fragility Curves for High Voltage Substations with Standard Components.

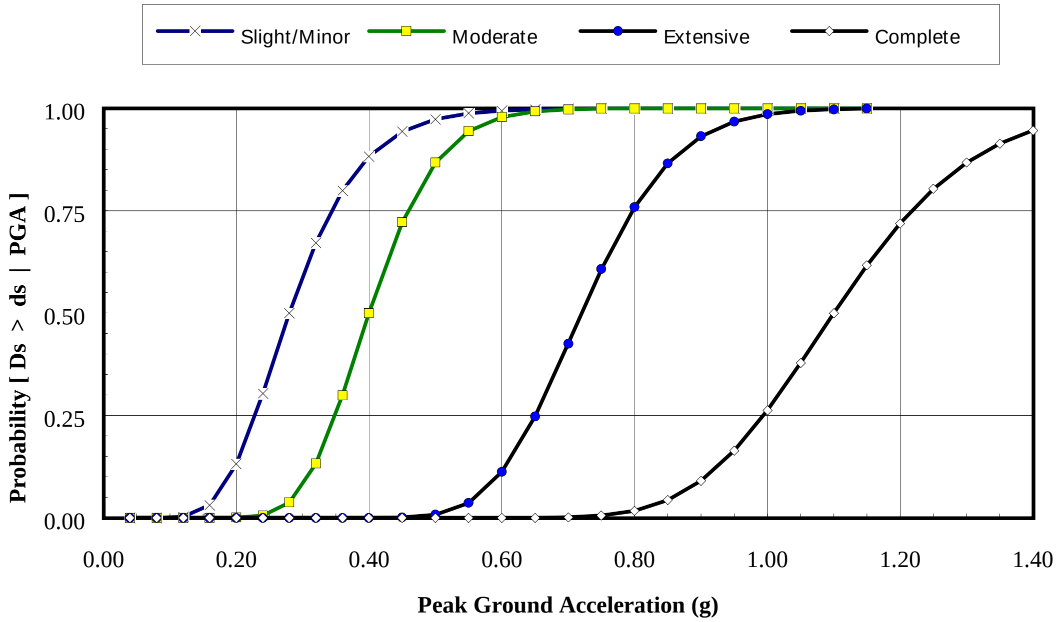


Figure 8.52: Fragility Curves for Seismic Distribution Circuits.

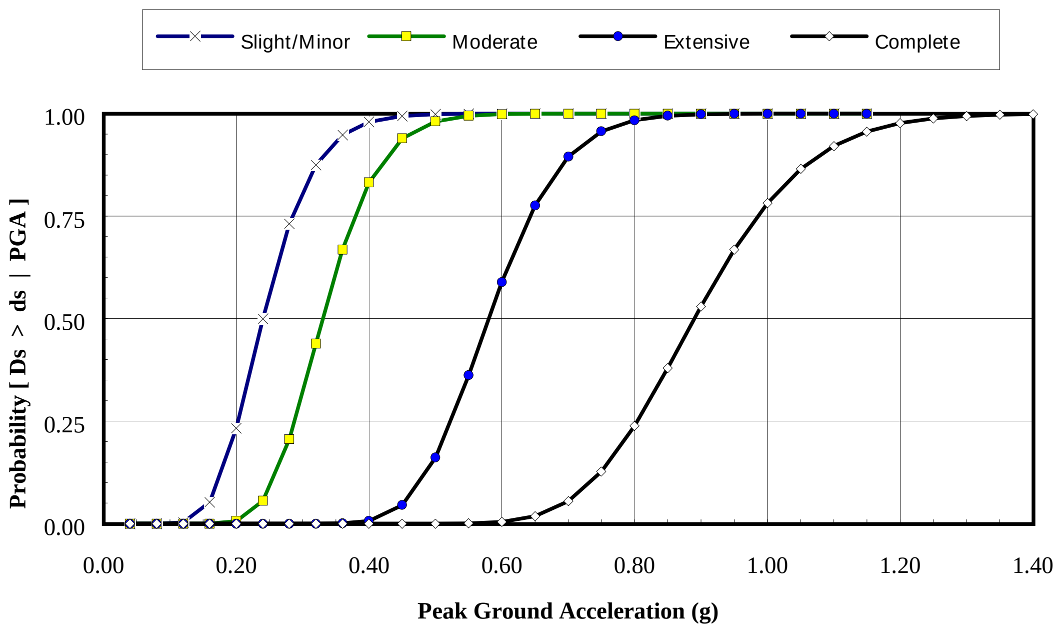


Figure 8.53: Fragility Curves for Standard Distribution Circuits.

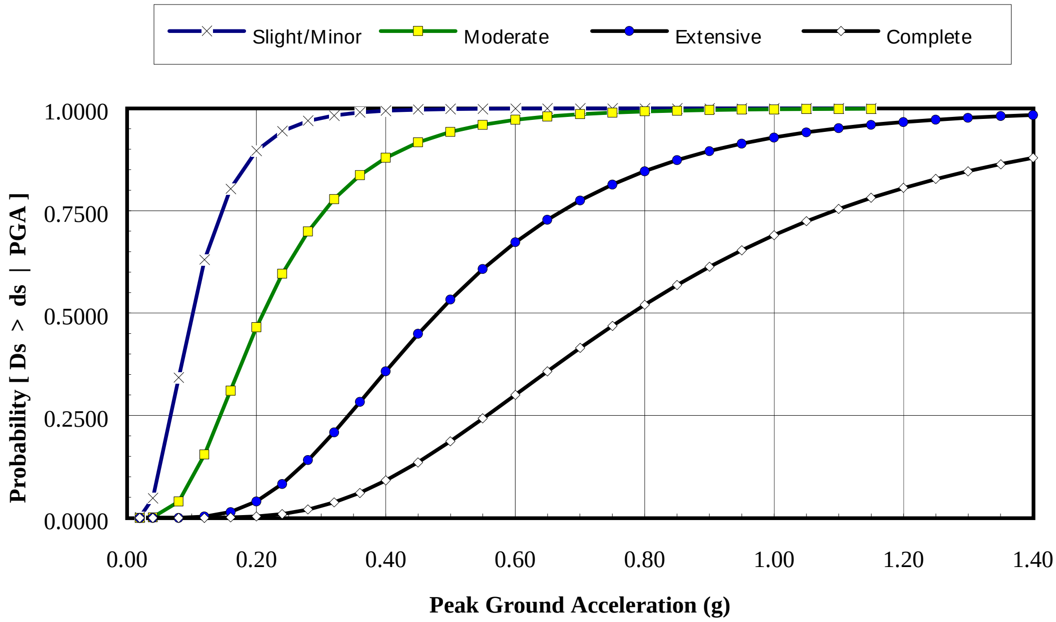


Figure 8.54: Fragility Curves for Small Generation Facilities with Anchored Components.

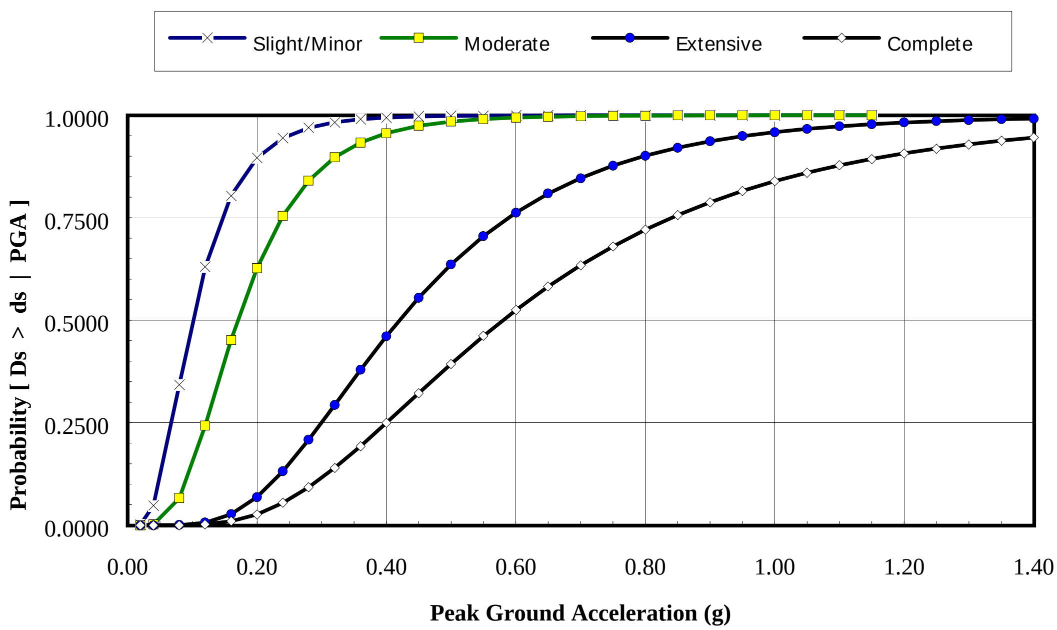


Figure 8.55: Fragility Curves for Small Generation Facilities with Unanchored Components.

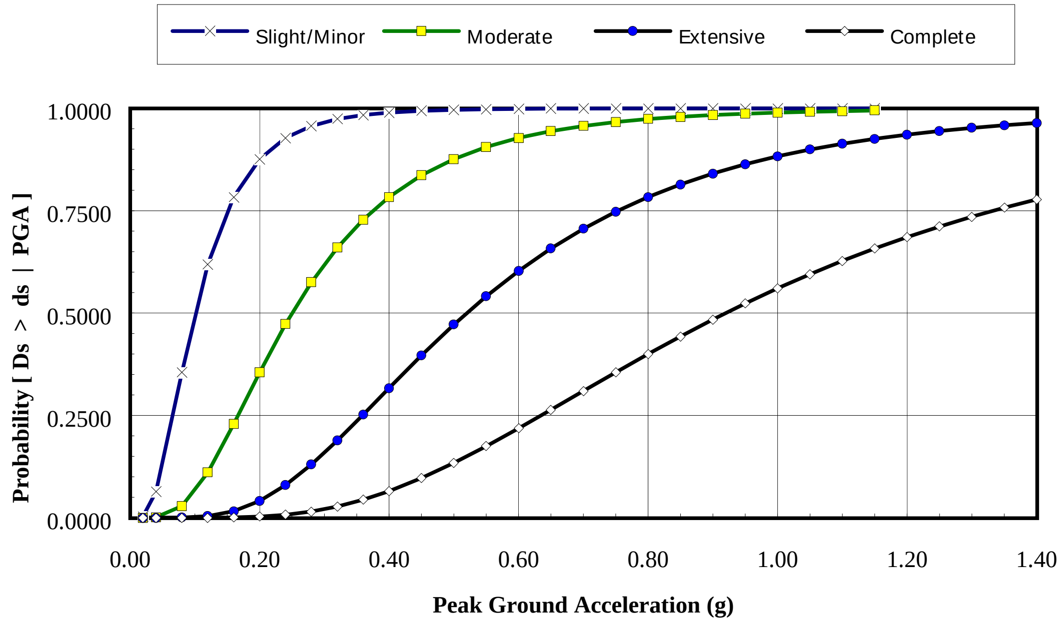


Figure 8.56: Fragility Curves for Medium/Large Generation Facilities with Anchored Components.

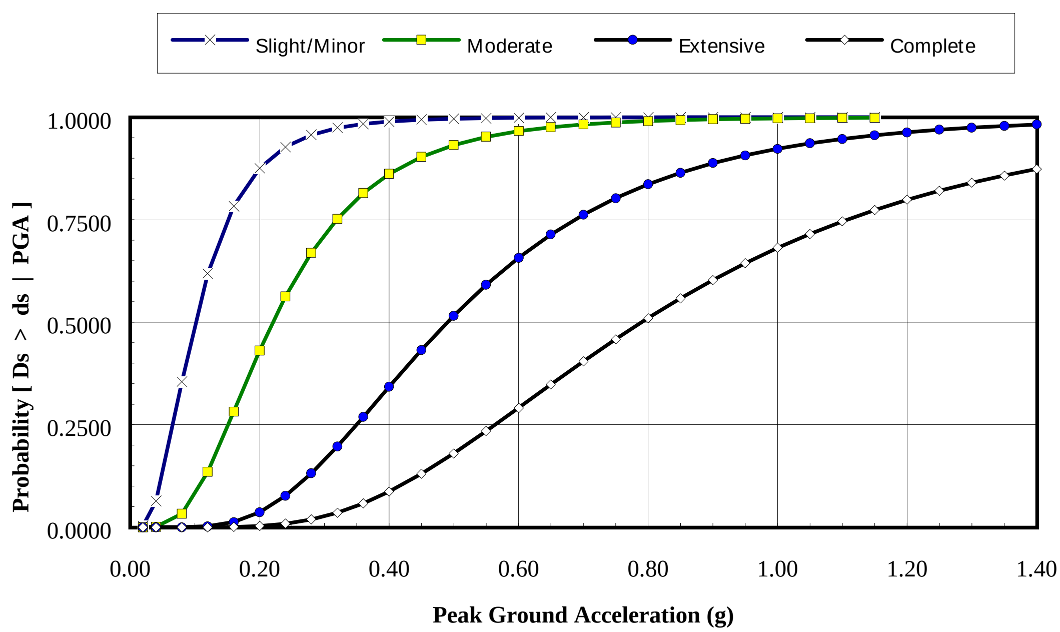


Figure 8.57: Fragility Curves for Medium/Large Generation Facilities with Unanchored Components.

8.6 Communication Systems

8.6.1 Introduction

This section presents the loss estimation methodology for communication systems during earthquakes. The major components of a communication system are:

- Central offices and broadcasting stations (this includes all subcomponents such as central switching equipment)
- Transmission lines (these include all subcomponents such as equipment used to connect central office to end users)
- Cabling (low capacity links)

Central offices and broadcasting stations are the only components of the communication system considered in this section. Therefore, fragility curves are presented for these components only. Other components, such as cables and other lines, usually have enough slack to accomodate ground shaking and even moderate amounts of permanent ground deformations.

8.6.2 Scope

The scope of this section includes development of methods for estimation of earthquake damage to a communication facility given knowledge of its subcomponents (i.e., building type, switching equipment, backup power and off-site power), classification (i.e., for equipment, anchored versus unanchored components), and the ground motion (i.e., peak ground acceleration and/or permanent ground deformation).

Damage states describing the level of damage to a communication facility are defined (i.e. slight, moderate, extensive or complete). Fragility curves are developed for each classification of the communication system component. These curves describe the probability of reaching or exceeding each damage state given the level of ground motion or ground failure. Restoration curves are also provided to evaluate the loss of function.

8.6.3 Input Requirements and Output Information

Required input to estimate damage to a communication system includes the following items:

- Geographical location of the communication facility (longitude and latitude)
- PGA
- Classification

Direct damage output for a communication system includes probability estimates of (1) component (i.e. central office / broadcasting station) functionality and (2) damage, expressed in terms of the component's damage ratio. Damage ratios for a communication facility are presented in section 15.3 of Chapter 15.

8.6.4 Form of Damage Functions

Damage functions or fragility curves for communication facilities are modeled as lognormally-distributed functions that give the probability of reaching or exceeding different damage states for a given level of ground motion (quantified in terms of PGA) and ground failure (quantified in terms of PGD). Each of these fragility curves is characterized by a median value of ground motion and an associated dispersion factor (lognormal standard deviation). Definitions of various damage states and the methodology used in deriving all these fragility curves are presented in the following section.

8.6.5 Description of Communication System Components

As it was mentioned previously, only facilities are considered. A communication facility consists of a building (generic type is assumed in the methodology), central switching equipment (i.e., digital switches, anchored or unanchored), and back-up power supply (i.e. diesel generators or battery generators, anchored or unanchored) that may be needed to supply the requisite power to the center in case of loss of off-site power.

8.6.6 Definitions of Damage States

Communication facilities are susceptible to earthquake damage. A total of five damage states are defined for these components. These are none (ds_1), slight/minor (ds_2), moderate (ds_3), extensive (ds_4) and complete (ds_5).

Slight/Minor Damage (ds_2)

- Slight damage, ds_2 is defined by slight damage to the communication facility building, or inability of the center to provide services during a short period (few days) due to loss of electric power and backup power, if available.

Moderate Damage (ds_3)

- Moderate damage, ds_3 is defined by moderate damage to the communication facility building, few digital switching boards being dislodged, or the central office being out of service for a few days due to loss of electric power (i.e., power failure) and backup power (typically due to overload), if available.

<u>Extensive Damage</u> (ds_4)

- Extensive damage, ds_4 is defined by severe damage to the communication facility building resulting in limited access to facility, or by many digital switching boards being dislodged, resulting in malfunction.

<u>Complete Damage</u> (ds_5)

- Complete damage, ds_5 is defined by complete damage to the communication facility building, or damage beyond repair to digital switching boards.

8.6.7 Component Restoration Curves

Restoration functions are shown in Figures 8.58, 8.59 and 8.60. Figure 8.58 is based on ATC-13 social function SF-33a (first four damage states). The curves in this figure are obtained in a similar manner to the restoration curves for other lifeline systems. The parameters of these restoration curves are given in Table 8.30.a and 8.30.b. The best-fit normal distribution to the data shown in Figure 8.59 has a mean of 3 days and a standard deviation of 3 days. This restoration curve corresponds to the case where (1) the communication facility building does not suffer extensive damage (major structural damage would require extended period of time to repair), and (2) the communication network did not suffer extensive damage. In essence, the plotted restoration curve in Figure 8.59 corresponds to the communication facility being in moderate to extensive damage state, according to the definitions of damage states presented herein.

Table 8.30.a: Continuous Restoration Functions for Communication Facilities (After ATC-13, 1985)

Restoration Functions (All Normal Distributions)			
Classification	**Damage State**	**Mean (Days)**	**σ**
Communication facility	slight/minor	0.5	0.2
	moderate	1	1.0
	extensive	7	7.0
	complete	40	40.0

Table 8.30.b: Discretized Restoration Functions for Communication Facilities

Discretized Restoration Functions						
Classification	**Damage State**	**1 day**	**3 days**	**7 days**	**30 days**	**90 days**
Communication facility	slight/minor	99	100	100	100	100
	moderate	50	98	100	100	100
	extensive	20	28	50	100	100
	complete	16	18	20	40	89

A recently published paper by Tang and Wong (1994) on the performance of telecommunication systems in the Northridge Earthquake of January 17, 1994 indicates that within three days the system stabilized. Table 8.31 shows the system performance during the three days following that quake.

Table 8.31: Daily Call Attempts as Recorded in a Central Office in the Afflicted Area (Tang and Wong, 1994)

	Daily Call Attempts in 1,000s				
	Jan 17	**Jan 18**	**Jan 19**	**Jan 20**	**1993 Average**
Call Attemtps	5,455	4,237	3,240	2,860	1,500
Performance	86.9%	95.2%	96.0%	97.6%	99.3%

8.6.8 Development of Damage Functions

In this subsection, damage functions for the central offices are presented. Fragility curves for these components are based on the probabilistic combination of subcomponent damage functions using Boolean expressions to describe the relationship of subcomponents to the component. It should be mentioned that the Boolean logic is implicitly presented within the definition of the damage state (see section 8.1.8 for an example). Note also that damage functions due to ground failure (i.e., PGD) for central offices are assumed to be similar to those described for potable water system facilities.

PGA related damage functions are given in terms of median values and dispersions for each damage state in Table 8.32. These are also plotted in Figures 8.61.a and 8.61.b.

Table 8.32: Damage Algorithms for Communication Facilities

Peak Ground Acceleration			
Classification	**Damage State**	**Median (g)**	**β**
Facilities with anchored components	slight/minor	0.15	0.75
	moderate	0.32	0.60
	extensive	0.60	0.62
	complete	1.25	0.65
Facilities with unanchored components	slight/minor	0.13	0.55
	moderate	0.26	0.50
	extensive	0.46	0.62
	complete	1.03	0.62

8.6.9 Guidance for Loss Estimation Using Advanced Data and Models Analysis

For this type of analysis, the expert can use the methodology developed for the User-Supplied Data Analysis with the flexibility to: (1) include a refined inventory of the communication system pertaining to the area of study, and (2) include specific and system specific fragility data. Default damage algorithms for User-Supplied Data Analysis, can be modified or replaced to accommodate any specified key component of a communication system, such as switching equipment. Similarly, better restoration curves could be developed given knowledge of the redundancy importance of a communication system components in the network, the availability of resources and a more accurate layout of the communication network within the local topographic and geological conditions.

8.6.10 References

(1) Tang A. and Wong F., "Observation on Telecommunications Lifeline Performance in the Northridge Earthquake of January 17, 1994, Magnitude 6.6", 1994.
(2) Tang A., "Two Decades of Communications Systems Seismic Protection Improvements", TCLEE Monograph No. 4 August, 1991.
(3) G&E Engineering Systems, Inc. (G&E), "NIBS Earthquake Loss Estimation Methods, Technical Manual, (Communication Systems)", June 1994.
(4) ATC-13, "Earthquake Damage Evaluation Data for California", Applied Technology Council, Redwood City, CA, 1985.

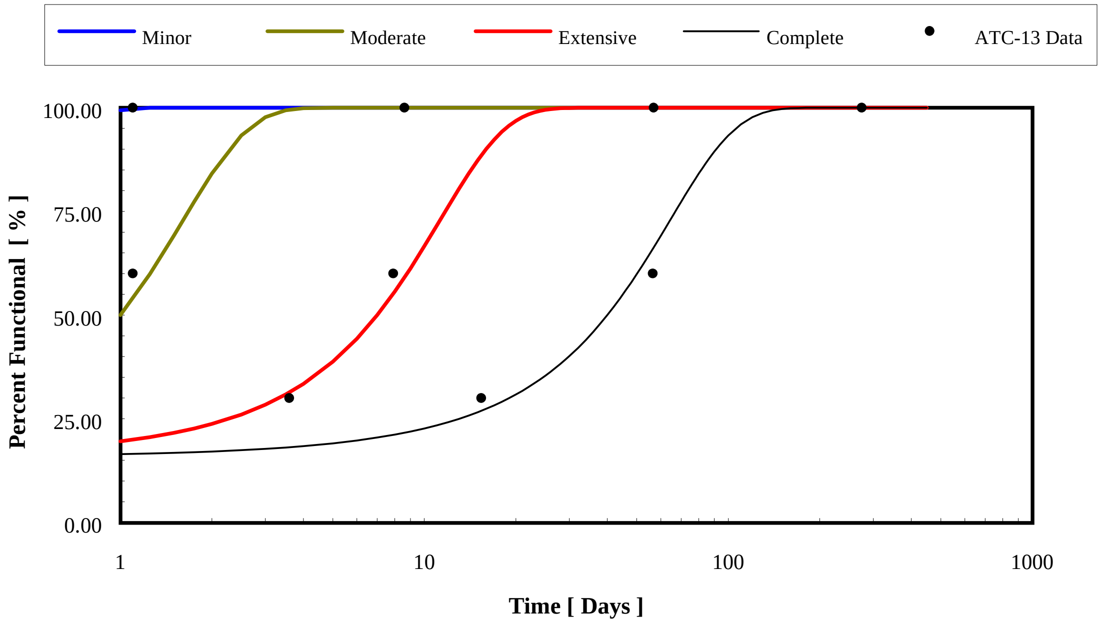


Figure 8.58: Restoration Curves for Central Offices (after ATC-13, 1985).

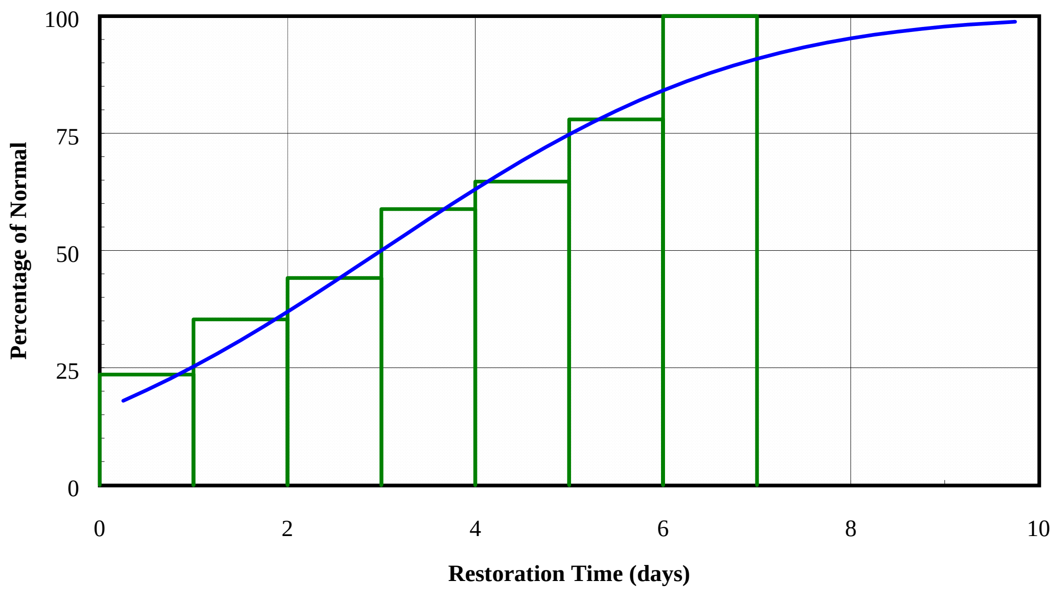


Figure 8.59: Restoration Curve for Communication System Service: Normal Service (After G&E, 1994).

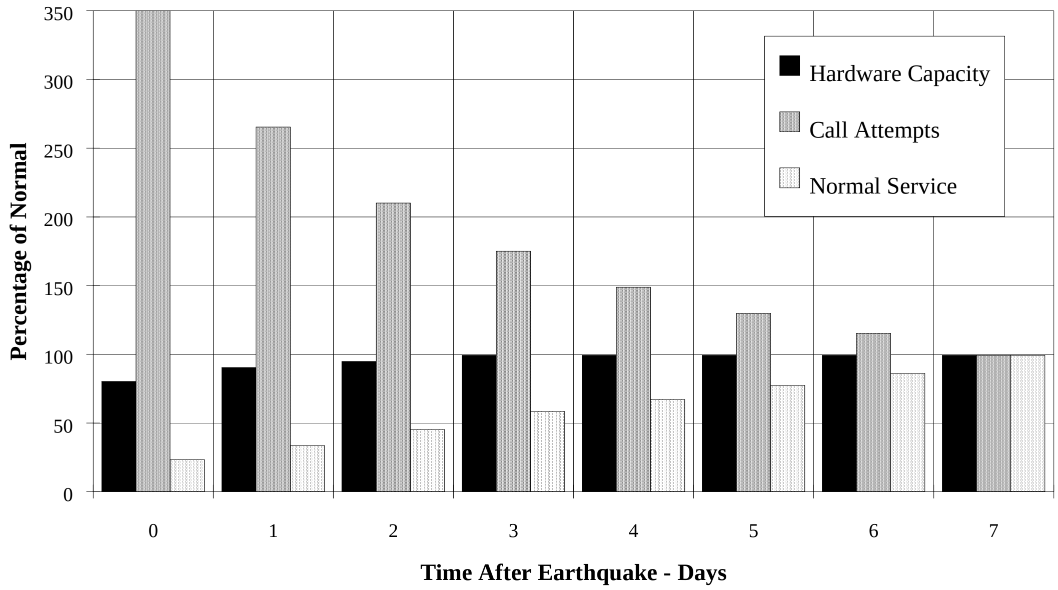


Figure 8.60: Communication System Service Restoration (after G&E, 1994).

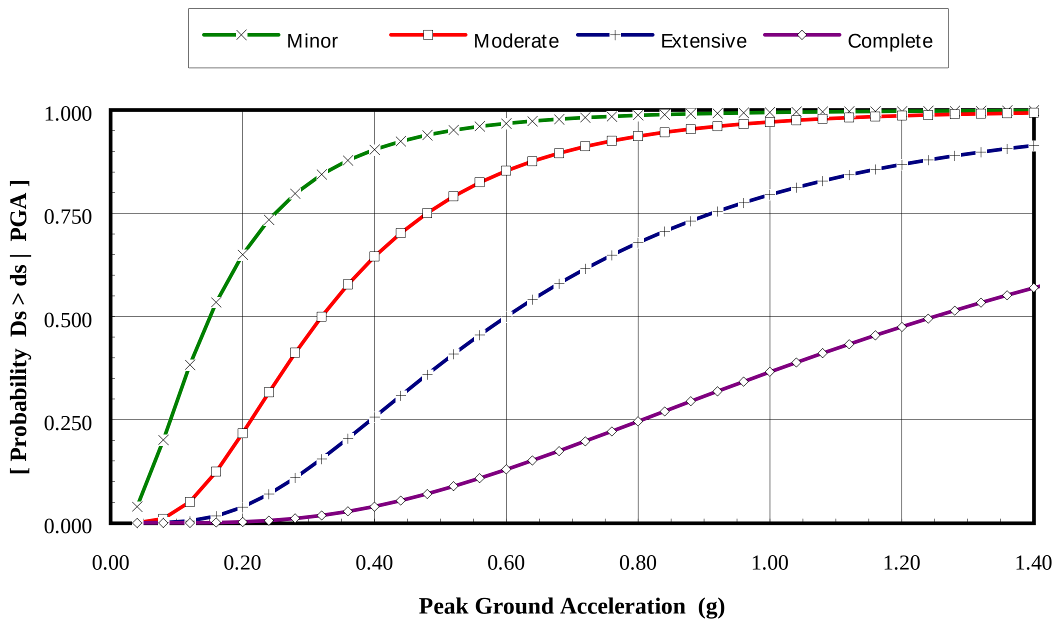


Figure 8.61.a: Fragility Curves for Communication Systems with Anchored Components.

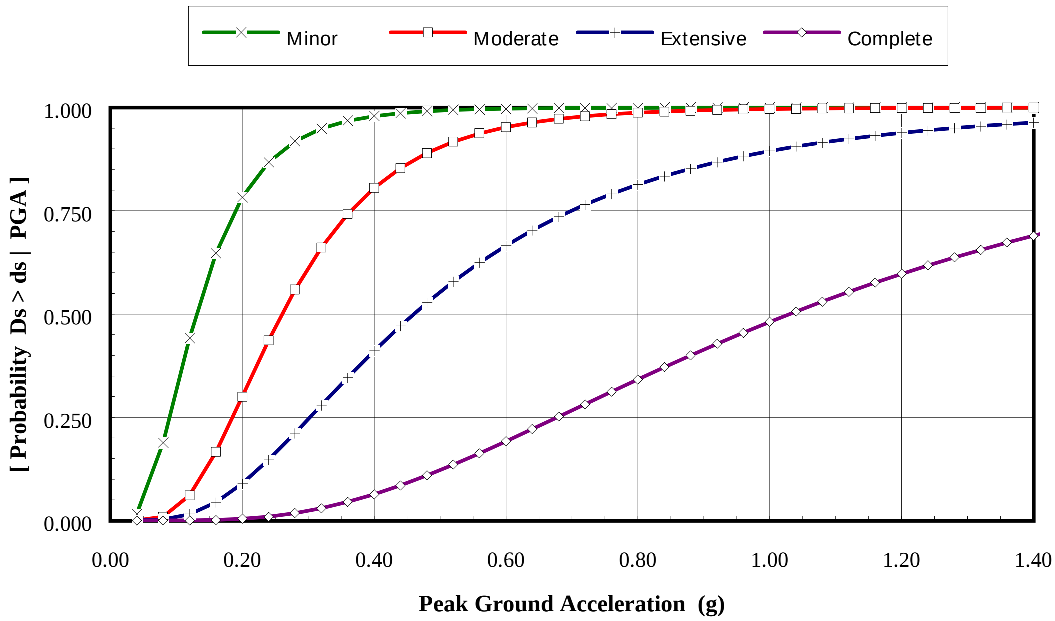


Figure 8.61.b: Fragility Curves for Communication Systems with Unanchored Components.

Appendix 8A
Subcomponent Damage Functions for Potable Water Systems

Any given subcomponent in the lifeline methodology can experience all five damage states; however, the only damage states listed in the appendices of Chapters 7 and 8 are the ones used in the fault tree logic of the damage state of interest of the component.

Table A.8.1: Subcomponent Damage Algorithms for Pumping Plants With Anchored Components (after G&E, 1994)

Peak Ground Acceleration			
Subcomponents	**Damage State**	**Median (g)**	**β**
Electric Power (Backup)	minor moderate	0.80 1.00	0.60 0.80
Loss of com-mercial Power	minor moderate	0.15 0.30	0.40 0.40
Vertical/ Horizontal Pump*	extensive	1.25/1.60	0.60
Building	minor moderate extensive complete	0.15 0.40 0.80 1.50	0.80 0.80 0.80 0.80
Equipment	moderate	1.00	0.60

* Difference in median values has little effect on the fault tree analysis

Table A.8.2: Subcomponent Damage Algorithms for Pumping Plants with Unanchored Components (after G&E, 1994)

Peak Ground Acceleration			
Subcomponents	**Damage State**	**Median (g)**	**β**
Electric Power (Backup)	minor moderate	0.20 0.40	0.60 0.80
Loss of commercial Power	minor moderate	0.15 0.30	0.40 0.40
Vertical/ Horizontal Pump*	extensive	1.25/1.60	0.60
Building	minor moderate extensive complete	0.15 0.40 0.80 1.50	0.80 0.80 0.80 0.80
Equipment	moderate	0.60	0.60

* Difference in median values has little effect on the fault tree analysis

Table A.8.3: Subcomponent Damage Algorithms for Wells with Anchored Components (after G&E 1994)

Peak Ground Acceleration			
Subcomponents	**Damage State**	**Median (g)**	**β**
Electric Power (Backup)	minor moderate	0.80 1.00	0.60 0.80
Loss of commercial Power	minor moderate	0.15 0.30	0.40 0.40
Well Pump	extensive	1.00	0.60
Building	minor moderate extensive complete	0.15 0.40 0.80 1.50	0.80 0.80 0.80 0.80
Electric Equipment	moderate	1.00	0.60

Table A.8.4: Subcomponent Damage Algorithms for Wells with Unanchored Components (after G&E 1994)

Peak Ground Acceleration			
Subcomponents	**Damage State**	**Median (g)**	**β**
Electric Power (Backup)	minor moderate	0.20 0.40	0.60 0.80
Loss of commercial Power	minor moderate	0.15 0.30	0.40 0.40
Well Pump	extensive	1.00	0.60
Building	minor moderate extensive complete	0.15 0.40 0.80 1.50	0.80 0.80 0.80 0.80
Electric Equipment	moderate	0.60	0.60

Table A.8.5: Subcomponent Damage Algorithms for Sedimentation/Flocculation System (after G&E 1994)

Peak Ground Acceleration			
Subcomponents	**Damage State**	**Median (g)**	**β**
Basins	minor	0.40	0.60
Baffles	minor	0.70	0.60
Paddles	moderate	0.80	0.60
Scrapers	moderate	0.90	0.60

Table A.8.6: Subcomponent Damage Algorithms for Water Treatment Plants with Anchored Components (after G&E 1994)

Peak Ground Acceleration			
Subcomponents	**Damage State**	**Median (g)**	**β**
Electric Power (Backup)	minor moderate	0.80 1.00	0.60 0.80
Loss of commercial Power	minor moderate	0.15 0.30	0.40 0.40
Chlorination Equipment	minor moderate	0.65 1.00	0.60 0.70
Sediment Flocculation	minor moderate	0.36 0.60	0.50 0.50
Chemical Tanks	minor moderate	0.40 0.65	0.70 0.70
Electric Equipment	moderate	1.00	0.60
Elevated Pipe	extensive complete	0.53 1.00	0.60 0.60
Filter Gallery	complete	2.00	1.00

Table A.8.7: Subcomponent Damage Algorithms for Water Treatment Plants with Unanchored Components (after G&E 1994)

Peak Ground Acceleration			
Subcomponents	**Damage State**	**Median (g)**	**β**
Electric Power (Backup)	minor moderate	0.20 0.40	0.60 0.80
Loss of com-mercial Power	minor moderate	0.15 0.30	0.40 0.40
Chlorination Equipment	minor moderate	0.35 0.70	0.60 0.70
Sediment Flocculation	minor moderate	0.36 0.60	0.50 0.50
Chemical Tanks	minor moderate	0.25 0.40	0.60 0.60
Electric Equipment	moderate	0.60	0.60
Elevated Pipe	extensive complete	0.53 1.00	0.60 0.60
Filter Gallery	complete	2.00	1.00

APPENDIX 8B
Subcomponent Damage Functions for Waste Water Systems

Table B.8.1: Subcomponent Damage Algorithms for Waste Water Treatment Plants with Anchored Components (after G&E, 1994)

Peak Ground Acceleration			
Subcomponents	**Damage State**	**Median (g)**	**β**
Electric Power (Backup)	minor moderate	0.80 1.00	0.60 0.80
Loss of commercial Power	minor moderate	0.15 0.30	0.40 0.40
Chlorination Equipment	minor moderate	0.65 1.00	0.60 0.70
Sediment Flocculation	minor moderate extensive	0.36 0.60 1.20	0.50 0.50 0.60
Chemical Tanks	minor moderate	0.40 0.65	0.70 0.70
Electrical/ Mechanical Equipment	moderate	1.00	0.60
Elevated Pipe	extensive complete	0.53 1.00	0.60 0.60
Buildings	complete	1.50	0.80

Table B.8.2: Subcomponent Damage Algorithms for Waste Water Treatment Plants with Unanchored Components (after G&E, 1994)

Peak Ground Acceleration			
Subcomponents	**Damage State**	**Median (g)**	**β**
Electric Power (Backup)	minor moderate	0.20 0.40	0.60 0.80
Loss of com-mercial Power	minor moderate	0.15 0.30	0.40 0.40
Chlorination Equipment	minor moderate	0.35 0.70	0.60 0.70
Sediment Flocculation	minor moderate extensive	0.36 0.60 1.20	0.50 0.50 0.60
Chemical Tanks	minor moderate	0.25 0.40	0.60 0.60
Electrical/ Mechanical Equipment	moderate	0.60	0.60
Elevated Pipe	extensive complete	0.53 1.00	0.60 0.60
Buildings	complete	1.50	0.80

APPENDIX 8C
Subcomponent Damage Functions for Oil Systems

Table C.8.1: Subcomponent Damage Algorithms for Refineries with Anchored Components (after G&E, 1994)

Peak Ground Acceleration			
Subcomponents	**Damage State**	**Median (g)**	**β**
ElectricPower (Backup)	minor moderate	0.80 1.00	0.60 0.80
Loss of com-mercial Power	minor moderate	0.15 0.30	0.40 0.40
Electrical/ Mechanical Equipment	moderate	1.00	0.60
Tanks	minor moderate extensive complete	0.30 0.70 1.25 1.60	0.60 0.60 0.65 0.60
Stacks	extensive	0.75	0.70
Elevated Pipe	complete	1.00	0.60

Table C.8.2: Subcomponent Damage Algorithms for Refineries with Unanchored Components (after G&E, 1994)

Peak Ground Acceleration			
Subcomponents	**Damage State**	**Median (g)**	**β**
Electric Power (Backup)	minor moderate	0.20 0.40	0.60 0.80
Loss of com-mercial Power	minor moderate	0.15 0.30	0.40 0.40
Electrical/ Mechanical Equipment	moderate	0.60	0.60
Tanks	minor moderate extensive complete	0.15 0.35 0.68 0.95	0.70 0.75 0.75 0.70
Stacks	extensive	0.60	0.70
Elevated Pipe	complete	1.00	0.60

Table C.8.3: Subcomponent Damage Algorithms for Pumping Plants with Anchored Components (after G&E, 1994)

Peak Ground Acceleration			
Subcomponents	**Damage State**	**Median (g)**	**β**
Electric Power (Backup)	minor moderate	0.80 1.00	0.60 0.80
Loss of commercial Power	minor moderate	0.15 0.30	0.40 0.40
Vertical/ Horiz. Pump*	extensive	1.25/1.60	0.60
Building	minor moderate extensive complete	0.15 0.40 0.80 1.50	0.80 0.80 0.80 0.80
Electrical/ Mechanical Equipment	moderate	1.00	0.60

* Difference in median values has little effect on the fault tree analysis

Table C.8.4: Subcomponent Damage Algorithms for Pumping Plants with Unanchored Components (after G&E, 1994)

Peak Ground Acceleration			
Subcomponents	**Damage State**	**Median (g)**	**β**
Electric Power (Backup)	minor moderate	0.20 0.40	0.60 0.80
Loss of commercial Power	minor moderate	0.15 0.30	0.40 0.40
Vertical/ Horizontal Pump*	extensive	1.25/1.60	0.60
Building	minor moderate extensive complete	0.15 0.40 0.80 1.50	0.80 0.80 0.80 0.80
Electrical/ Mechanical Equipment	moderate	0.60	0.60

- Difference in median values has little effect on the fault tree analysis

Table C.8.5: Subcomponent Damage Algorithms for Tank Farms with Anchored Components (after G&E, 1994)

Peak Ground Acceleration			
Subcomponents	**Damage State**	**Median (g)**	**β**
ElectricPower (Backup)	minor moderate	0.80 1.00	0.60 0.80
Loss of com-mercial Power	minor moderate	0.15 0.30	0.40 0.40
Electrical/ Mechanical Equipment	moderate	1.00	0.60
Tanks	minor moderate extensive complete	0.30 0.70 1.25 1.60	0.60 0.60 0.65 0.60
Elevated Pipes	extensive complete	0.53 1.00	0.60 0.60

Table C.8.6: Subcomponent Damage Algorithms for Tank Farms with Unanchored Components (after G&E, 1994)

Peak Ground Acceleration			
Subcomponents	**Damage State**	**Median (g)**	**β**
ElectricPower (Backup)	minor moderate	0.20 0.40	0.60 0.80
Loss of Com-mercial Power	minor moderate	0.15 0.30	0.40 0.40
Electrical/ Mechanical Equipment	moderate	0.60	0.60
Tanks	minor moderate extensive complete	0.15 0.35 0.68 0.95	0.70 0.75 0.75 0.70
Elevated Pipes	extensive complete	0.53 1.00	0.60 0.60

APPENDIX 8D
Subcomponent Damage Functions for Electric Power Systems

Table D.8.1: Damage Algorithms for Subcomponents of Low Voltage Substations with Anchored Subcomponents (after G&E, 1994)

Peak Ground Acceleration			
Classification	**Damage State**	**Median (g)**	**β**
Transformer	All*	0.75	0.70
Disconnect Switches	All*	1.20	0.70
Live Tank Circuit Breaker	All*	1.0	0.70
Current Transformer	All*	0.75	0.70

* Damage state depends on the percentage of the subcomponents failing

Table D.8.2: Damage Algorithms for Subcomponents of Low Voltage Substations with Unanchored Subcomponents (after G&E, 1994)

Peak Ground Acceleration			
Classification	**Damage State**	**Median (g)**	**β**
Transformer	All*	0.50	0.70
Disconnect Switches	All*	0.90	0.70
Live Tank Circuit Breaker	All*	0.60	0.70
Current Transformer	All*	0.75	0.70

* Damage state depends on the percentage of the subcomponents failing

Table D.8.3: Damage Algorithms for Subcomponents of Medium Voltage Substations with Anchored Subcomponents (after G&E, 1994)

Peak Ground Acceleration			
Classification	**Damage State**	**Median (g)**	**β**
Transformer	All*	0.60	0.70
Disconnect Switches	All*	0.75	0.70
Live Tank Circuit Breaker	All*	0.70	0.70
Current Transformer	All*	0.50	0.70

* Damage state depends on the percentage of the subcomponents failing

Table D.8.4: Damage Algorithms for Subcomponents of Medium Voltage Substations with Unnchored Subcomponents (after G&E, 1994)

Peak Ground Acceleration			
Classification	**Damage State**	**Median (g)**	**β**
Transformer	All*	0.30	0.70
Disconnect Switches	All*	0.50	0.70
Live Tank Circuit Breaker	All*	0.50	0.70
Current Transformer	All*	0.50	0.70

* Damage state depends on the percentage of the subcomponents failing

Table D.8.5: Damage Algorithms for Subcomponents of High Voltage Substations with Anchored Subcomponents (after G&E, 1994)

Peak Ground Acceleration			
Classification	**Damage State**	**Median (g)**	**β**
Transformer	All*	0.40	0.70
Disconnect Switches	All*	0.60	0.70
Live Tank Circuit Breaker	All*	0.40	0.70
Current Transformer	All*	0.30	0.70

* Damage state depends on the percentage of the subcomponents failing

Table D.8.6: Damage Algorithms for Subcomponents of High Voltage Substations with Unnchored Subcomponents

Peak Ground Acceleration			
Classification	**Damage State**	**Median (g)**	**β**
Transformer	All*	0.25	0.70
Disconnect Switches	All*	0.40	0.70
Live Tank Circuit Breaker	All*	0.30	0.70
Current Transformer	All*	0.30	0.70

* Damage state depends on the percentage of the subcomponents failing

Table D.8.7: Damage Algorithms for Distribution Circuits (after G&E, 1994)

Peak Ground Acceleration			
Classification	**Damage State**	**Median (g)**	**β**
Seismic	All*	0.75	0.50
Standard	All*	0.60	0.50

* Damage state depends on the percentage of the subcomponents failing

Table D.8.8: Damage Algorithms for Subcomponents of Generation Facilities with Anchored Subcomponents (after G&E, 1994)

Peak Ground Acceleration			
Classification	**Damage State**	**Median (g)**	**β**
Electrical Equipment	minor moderate	0.30 0.50	0.40 0.60
Boilers & Pressure vessels	Moderate	0.52	0.70
Large vertical vessels with formed heads	Moderate Extensive	0.60 0.88	0.40 0.39
Motor Driven Pumps	Extensive	1.28	0.34
Large horizontal vessels	Complete	1.56	0.61
Large motor operated valves	Complete	1.93	0.65
Boiler Building	minor moderate extensive complete	0.15 0.40 0.80 1.50	0.80 0.80 0.80 0.80
Turbine Building	minor moderate extensive complete	0.15 0.40 0.80 1.50	0.80 0.80 0.80 0.80

Table D.8.9: Damage Algorithms for Subcomponents of Generation Facilities with Unanchored Subcomponents (after G&E, 1994)

Peak Ground Acceleration			
Classification	**Damage State**	**Median (g)**	**β**
Electrical Equipment	minor moderate	0.22 0.35	0.50 0.70
Boilers & Pressure vessels	Moderate	0.36	0.70
Large vertical vessels with formed heads	Moderate Extensive	0.46 0.68	0.50 0.48
Motor Driven Pumps	Extensive	1.00	0.43
Large horizontal vessels	Complete	1.05	0.75
Large motor operated valves	Complete	1.23	0.80
Boiler Building	minor moderate extensive complete	0.15 0.40 0.80 1.50	0.80 0.80 0.80 0.80
Turbine Building	minor moderate extensive complete	0.15 0.40 0.80 1.50	0.80 0.80 0.80 0.80

APPENDIX 8E
Subcomponent Damage Functions for Communication Systems

Table E.8.1: Subcomponent Damage Algorithms for Communication Systems with Anchored Components

Peak Ground Acceleration			
Subcomponents	**Damage State**	**Median (g)**	**β**
Electric Power (Backup)	slight moderate	0.80 1.00	0.60 0.80
Loss of commercial Power	minor moderate	0.15 0.30	0.40 0.40
Switching Equipment	moderate extensive complete	0.70 1.00 2.53	0.70 0.70 0.70
Building	slight moderate extensive complete	0.15 0.40 0.80 1.50	0.80 0.80 0.80 0.80

Table E.8.2: Subcomponent Damage Algorithms for Communication Systems with Unanchored Components

Peak Ground Acceleration			
Subcomponents	**Damage State**	**Median (g)**	**β**
Electric Power (Backup)	slight moderate	0.20 0.40	0.60 0.80
Loss of commercial Power	minor moderate	0.15 0.30	0.40 0.40
Switching Equipment	moderate extensive complete	0.45 0.62 1.58	0.70 0.70 0.70
Building	slight moderate extensive complete	0.15 0.40 0.80 1.50	0.80 0.80 0.80 0.80

Chapter 9
Induced Damage Models - Inundation

9.1 Introduction

Flood-induced damage in an earthquake can result from tsunamis (seismic sea waves), seiches (sloshing effects in lakes and bays) or dam or levee failure. Especially in the case of dams and levees, a single structure's failure could result in large losses, which implies that a site-specific analysis should be done rather than using the methodology, which is designed to estimate losses based on probabilities of performance across large inventories. Therefore, the potential exposure to earthquake-caused inundation is computed in the methodology, while prediction of losses or the likelihood of losses is excluded. Figure 9.1 illustrates the relationship of the inundation module to other modules in the methodology.

9.1.1 Scope

The purpose of this module provides the methods for assessing inundation loss potential due to dam and levee failure, tsunami and seiche. For each of these hazards, various levels of results can be obtained according to the complexity of the evaluation, data requirements, and the use of expert assistance to perform the assessment.

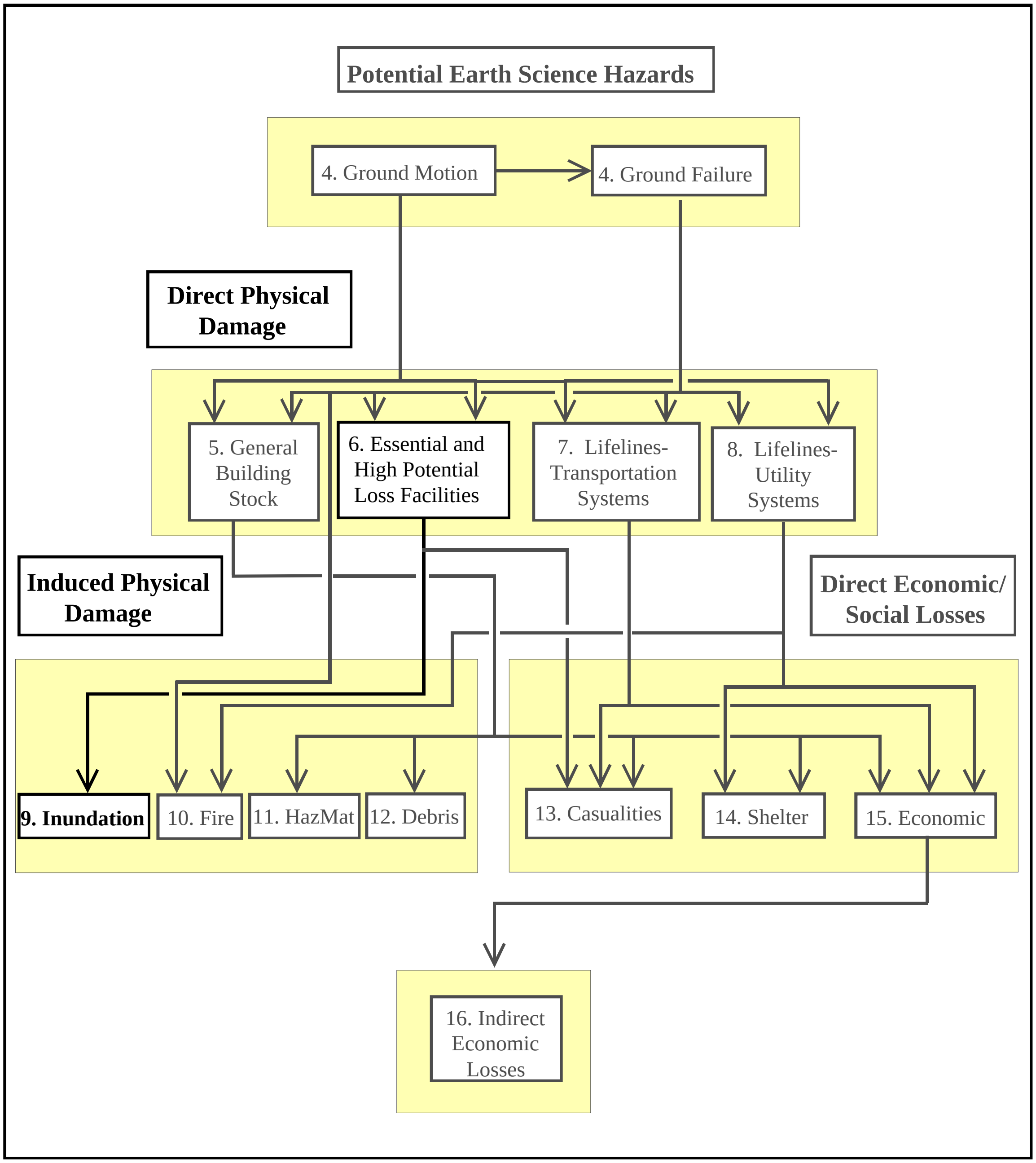
The purpose of this module is to identify the potential sources of flooding in a study area and overlays existing inundation maps with other data to identify the potential exposure. If existing inundation maps are not available, creating inundation maps will require the involvement of experts to perform sophisticated evaluations.

9.1.2 Form of Inundation Estimate

In using existing inundation maps care must be taken in interpreting the results. These maps usually are based on worst-case assumptions, such as a dam being completely full and failing catastrophically, and rarely is such a scenario tied to a specific earthquake scenario.

In general, a complete characterization of flood hazard includes an assessment of:

- Area of inundation
- Depth and velocity of flooding
- Arrival time of the flood following the occurrence of the earthquake, such as in the case of a dam or levee failure or tsunami
- Probability of the above described event



Flowchart 9.1: Relationship of inundation Module to other Modules in the Earthquake Loss Estimation Methodology

The information on inundation that is reported will vary from analysis to analysis. Only in a detailed engineering analysis, as described above, is a complete characterization of the inundation provided.

For each source of flooding (dam or levee failure, tsunami and seiche), the primary format for the presentation of the hazard will be an inundation map. An inundation map identifies the bounds of the area that will be inundated. The bounds can be used to evaluate the population and economic values in the affected area. When digitized for entry into a GIS system, the area of inundation could be overlaid with a topographic map to infer the depth of flooding. However, in the current methodology, this capability does not exist. Figure 9.1 provides an example of an inundation map.

9.1.3 Input Requirements and Output Information

This subsection defines the input requirements and output information for the induced damage inundation module. Subsection 9.1.3.1 describes the input requirements, followed by subsection 9.1.3.2 providing the output information.

9.1.3.1 Input Requirements

9.1.3.1.1 Dam Failure

The input information comes from a default database developed from the National Inventory of Dams database (NATDAM) [FEMA, 1993]. The database identifies all dams in the United States that satisfy the minimum size or hazard criteria given in Table 9.1. For each dam, the database contains multiple fields of information related to the dam and the body of water impounded by the dam. Hazard classifications are found in Section 9.1.3.2.1. Where they exist, inundation maps can be collected. The availability of inundation maps can be determined by contacting the following organizations:

- State or federal dam safety or water resources regulatory agencies
- State office of emergency services
- Local emergency services, law enforcement, or fire protection agencies
- Dam owner (which may be a private individual or organization or public agency such as the U.S. Army Corps of Engineers or Bureau of Reclamation).

Table 9.1 National Inventory of Dam - Size and Hazard Criteria

Category	Criterion	Excluded
Dam Height	Structural Height (H) $\geq$ 25 ft.	C $\leq$ 15 acre-feet maximum capacity regardless of dam height
Reservoir Size	Reservoir Impoundment Capacity (C) $\geq$ 50 acre-feet	H $\leq$ 6 feet regardless of reservoir capacity
Hazard	Any dam that poses a "significant" threat to human life or property in the event of its failure.	

9.1.3.1.2 Levee Failure

Unlike dams, a national inventory for levees does not exist. The user must contact local sources to identify levees in the study region. Possible sources include United States Army Corps of Engineers district offices, local flood, reclamation, or levee maintenance control districts, the United States Soil Conservation Service, and municipal or county authorities. The user must provide the geographical location of the levees (represented in the methodology software as polylines). Additional information that should be included in the levee inventory includes the levee design basis (e.g., 100 year flood), the levee crest elevations, normal water level elevation, and levee owner/operator.

Since most levees and in some locations floodwalls are designed to provide protection during periods of flooding, they are typically dry (i.e., do not impound/retain water) at the majority of the time. As a result, seismic failure of a levee during non-flood conditions does not pose an inundation hazard. As part of the process of identifying levees in the study region, the user should also obtain information as to whether the levee is dry the majority of the year (e.g. greater than 75% of the time). If this is the case, the levee might be screened out from further consideration, unless a study of the worst-case scenario is desired

Existing levee inundation maps are used to identify areas that may be flooded in the case of a failure. It is unlikely that an existing levee inundation study will be available. If a study is available, it should be reviewed to determine whether the water level used is consistent with the level that can be expected when an earthquake occurs.

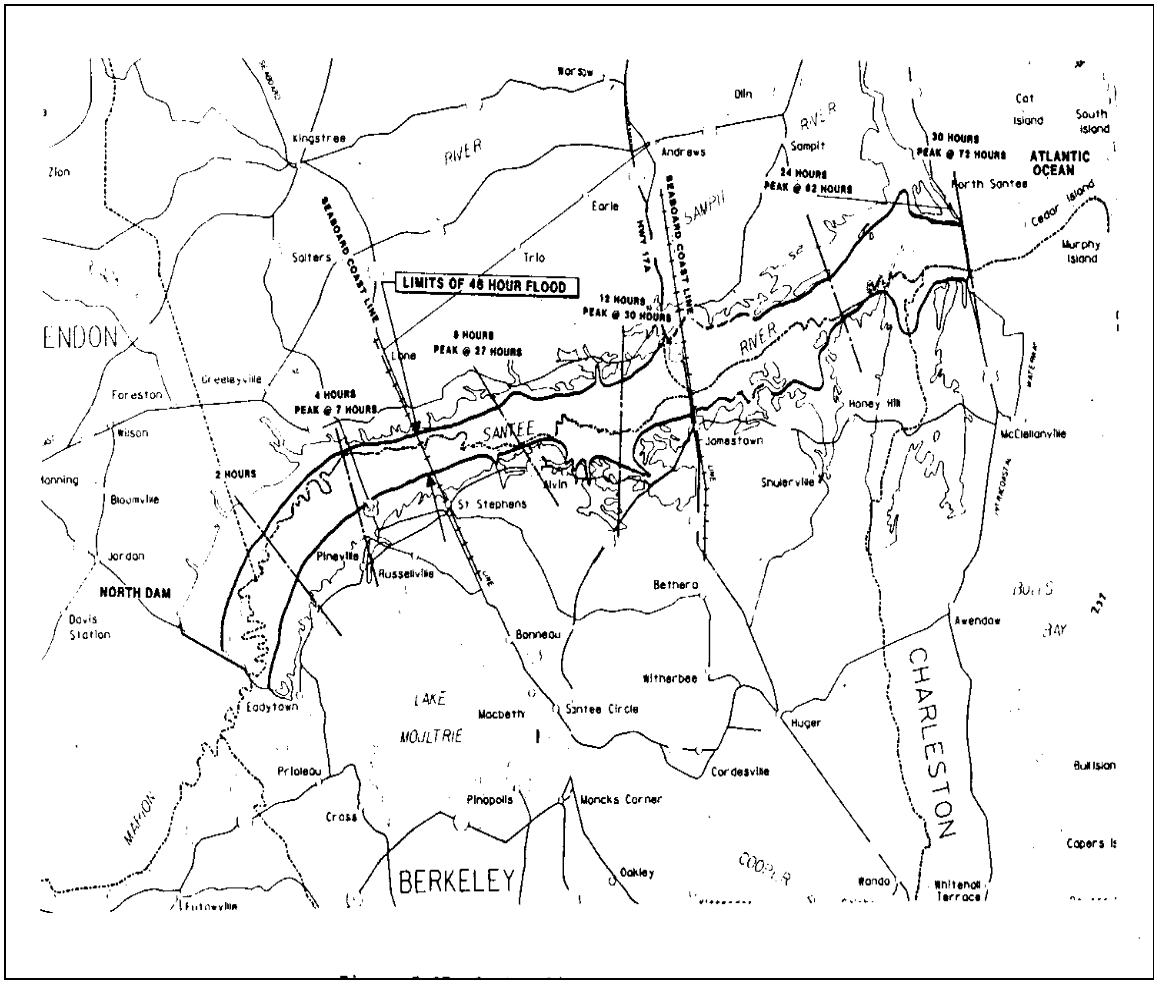


Figure 9.1 Dam failure inundation map.

9.1.3.1.3 Input Requirements - Tsunami

The first objective in the analysis of tsunami is to simply identify whether a tsunami hazard exists. To accomplish this, the following information is needed.

- Location of the earthquake (on-shore or off-shore event)
- Type of faulting

If the earthquake source is on-shore there is no tsunami hazard. The same is true if an offshore event occurs that involves primarily strike-slip movement. Alternatively, if the earthquake occurs offshore and significant vertical displacement of the seafloor occurs and a tsunami exists. The assessment of tsunami inundation in the methodology is for nearby seismic events only. Tsunami inundation maps based on distant events should not be combined with the study region scenarios. For example, a tsunami affecting the West Coast generated by and earthquake in Alaska should not be combined with the study of losses occurring from an earthquake in Los Angeles.

The user should determine the size and location of the earthquake that was assumed to estimate the tsunami inundation or, if specified, the mean return period of the tsunami. This will provide a basis to judge whether the existing inundation map conservatively or un-conservatively estimates the inundation that would be produced by the study earthquake. In cases where a scenario earthquake would generate a tsunami, the probability basis of the tsunami inundation map should match that of the scenario earthquake. For example, if an existing tsunami inundation map based on wave run-ups caused by local earthquake that have a mean return period of 500 years for a study region in Alaska, then the scenario earthquake selected for use with the methodology should also have a 500 year return period. Otherwise, the tsunami and the earthquake loss outputs should not be combined because this would describe different events.

9.1.3.1.4 Input Requirements - Seiche

To first step in seiche analysis is to identify natural or man-made bodies of water where a seiche may be generated. The default database of dams can be used to identify the man-made bodies of water (see Section 9.1.3.1.1) while the user must generate an inventory of natural water bodies in the study region. The following criteria can be used to identify bodies of water that should be considered in the assessment:

- The lake volume must be greater than 500,000 acre-feet
- There must be an existing population and/or property located in proximity to the lake shore that could be inundated

If these criteria are not met, lakes should not be considered for assessment. Existing seiche inundation maps are used to identify areas subject to flooding. Sources of existing seiche inundation studies include state and federal agencies that regulate dams, dam or lake owners, and state office of emergency services. The availability of such studies is very limited.

9.1.3.2 Output Information

The output of the dam failure inundation module consists of an inventory of the dams located in the study region divided into three groups corresponding to the hazard classifications provided in the database. The hazard classification system is shown in the Table 9.2 below.

Table 9.2 Dam Hazard Classifications

Hazard	Urban Development	Economic Loss
Low	No permanent structures for human habitation	Minimal (undeveloped to occasional structures or agriculture)
Significant	Urban development and no more than a small number of inhabitable structures	Appreciable (notable agriculture, industry)
High	Urban development with more than a small number of inhabitable structures	Serious (extensive community, industry or agriculture)

In addition to the inventory of dams located in the study region, the analysis will utilize existing digital dam inundation maps to identify the population and property at risk due to the dam failure.

The output of levees analysis is an inventory of the levees in the study region whose failure could lead to flooding. In addition to the inventory of levees located in the study region, analysis can use existing digital levee, tsunami, and seiche inundation maps (limited availability) to quantify the population and property at risk due to the failure of levees.

9.2 Description of Methodology

9.2.1 Dam Failure

This subsection describes the approach used to perform analyses for inundation due to dam failure. To start the analysis of dams, the dams that are located in the study region have to be identified. To do this, a geographic search through the default dam database is conducted. Based on the dam hazard classification, a list of the Low, Significant and High Hazard dams can generated. Note that “hazard” here means the danger posed if the dam fails, and is not a description of the probability of such failure. Next, an analysis using existing digital inundation maps is conducted to estimate the potential population and economic value impacted by a dam failure.

9.2.2 Levee Failure

The tasks and analysis tools are similar to those required for dam failure. An inventory of levees located in the study region is generated by contacting local, state and federal agencies. The inventory should typically include levees that act as water barriers greater than 10 percent of the time. This excludes from the inventory levees that remain dry except during short periods of flooding, because of the small probability the earthquake will coincide with a time of high water level. Existing levee failure inundation studies are used to identify areas that may be impacted by levee failure. When using existing inundation studies, the following should be considered:

- Existing inundation studies must be reviewed to determine assumptions regarding water levels
- The analyst should identify areas where levee failure will have the most severe impact; existing studies may not have used this approach

9.2.3 Tsunami

This subsection describes the approach to perform evaluations for inundation due to tsunami. Existing tsunami studies may include inundation maps for the scenario earthquake. However, they should be reviewed to verify the assumptions on which the tsunami was based. As explained above, tsunami inundation maps developed for distant earthquakes should not be used in combination with a local scenario event. However, the methodology can be used to independently estimate the population and building value at risk from a distant event tsunami simply by using a representative inundation map in which case these results would not be combined with those of a local earthquake scenario.

9.2.4 Seiche

This subsection describes the approach to perform evaluations for inundation due to seiche. Existing seiche inundation studies are used to identify the areas where flooding may occur. However, in most cases such studies do not exist. In some cases the results of a seiche analysis may be available that did not produce an inundation map. In this case, the user could transfer the results to a topographic map of the lakeshore area to determine the bounds of inundation.

9.3 Guidance for Expert-Generated Estimates

Losses that might be caused by earthquake-caused flooding are not calculated within the methodology, because of the facility-specific evaluation by experts that is necessary. The information in this section is not intended to supplant the need for experts when a loss study is extended into these induced hazards, but rather to provide these civil engineering, hydrological, and geotechnical experts guidance to standardize their analyses.

9.3.1 Dam Failure

The greatest uncertainty lies in the likely cause, mode, degree and time sequence of failure. Another uncertainty involves flood routing and limits of inundation downstream of the failed dams. Although several historical dam failures have been documented, very few have provided an exact description of the hydraulics of the failure flood.

The hydraulic characteristics of a surge released from a dam failure depends on the size, shape and position of the breach, volume of water stored behind the dam, the dam height, width and length of the reservoir, and the reservoir inflow and tailwater condition at the time of the failure. To provide uniformity in the evaluation of the effects of dam failure during a seismic event, the following guidelines are provided. These guidelines should be followed unless deviations are appropriate in the opinion of an expert analyst.

Antecedent Conditions - Reservoir levels generally predictably related to the purpose of the reservoir. Whereas a seismic event can occur anytime during the year, the following guidance is provided:

1. Reservoir Conditions - It should be assumed that the reservoir is at the average operational level for the season when water levels are highest. If the average operational level is not known, the maximum normal depth of water should be used.
2. Antecedent Flow - Unless a dam has failed due to failure of an upstream dam, the antecedent stream flow into the reservoir is assumed equivalent to the mean monthly flow for the season assumed for the scenario. If the failure is assumed to occur during the flood season, then the mean annual flood for the month is assumed. This antecedent flow can also be applied as the base flow downstream of the dam.

Tailwater Condition - No assumption on the varying tailwater condition is necessary when using DAMBRK, a program developed by the National Weather Service (NWS), because the model automatically calculates the tailwater elevation based on the base flow and outflow from the spillway or breach formation. The model does appropriate correction for submergence automatically.

River Cross-Section - For the purpose of representing the river channel in the DAMBRK model (see Figure 9.2), cross-sections of the river at selected critical stations are normally taken from U.S.G.S. 7 1/2 minute topographic maps. Since only 8 elevation-top-widths data points can be accepted by DAMBRK, care should be used in selecting cross-section data for the stations along the river or valleys to assure accurate estimates of flood elevations.

Mode of Failure - A conservative estimate of flooding due to a dam failure would assume complete disappearance of the dam. For small concrete dams, such an assumption may be reasonable. However, for large concrete gravity dams, it is more reasonable to assume partial breach with some parts of the dam remaining intact. For example, embankment dams will generally fail by erosion.

Shape and Size of Failure - Breach shapes are assumed to follow regular geometrical shapes such as a triangle, rectangle, trapezoid, or parabolic figure. Failure depth is always assumed equal to the total height of the dam unless there is a high tailwater.

Table 9.3 gives guidance on the various parameters that could be assumed for a given breach shape and size.

Time to Maximum Failure - This is one of the most unpredictable parameters in dam break modeling. To facilitate the adoption of reasonable values of time to maximum failure, Table 9.3 gives recommended values for various types of dams.

Expansion and Contraction Coefficients - The manual for DAMBRK recommends values of cross-section contraction/expansion coefficients for the contraction or expansion of the downstream reach's cross-sectional geometry. Contraction values generally vary from 0.1 to 0.3 while expansion values usually vary from -1.0 to -0.1. If contraction-expansion effects are negligible, a value of 0.1 is used.

Table 9.3 Suggested Breach Characteristics (see Figure 9.3)
(Fread, 1982)

Parameter	Value	Type of Dam
Average Breach Width (BR)	W = Crest Length H = Dam Height BR = Width of 1 or more monoliths, usually BR $\leq$ 0.50W HD < BR $\leq$ 5HD (usually between 2HD and 4HD) BR > 0.8 Crest Length	Arch Masonry, Gravity Earthen, Rockfill, Timber Crib Slag, Refuse
Horizontal Component of the Side Slope of Breach (Z)	0<Z$\leq$ Slope of the Valley Walls Z = 0 1/4 < Z $\leq$ 1 1 < Z $\leq$ 2	Arch Masonry, Gravity, Timber Crib Earthen (engineered compacted) Slag, Refuse (non-engineered)
Time to Failure (TFH) (hours)	TFH < 0.10 0.1 < TFH $\leq$ 0.3 0.1 < TFH $\leq$ 1.0 0.1 < TFH $\leq$ 0.5 0.1 < TFH $\leq$ 0.3	Arch Masonry, Gravity Earthen (engineered compacted), Timber Crib Earthen (non-engineered, poor construction) Slag, Refuse

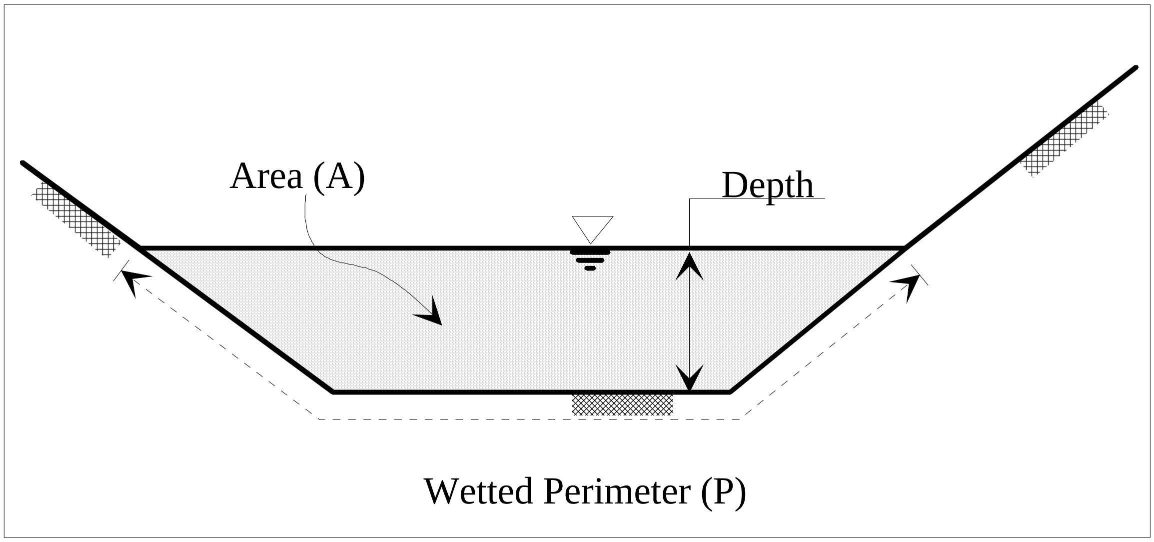


Figure 9.2 Illustration of a channel cross-section.

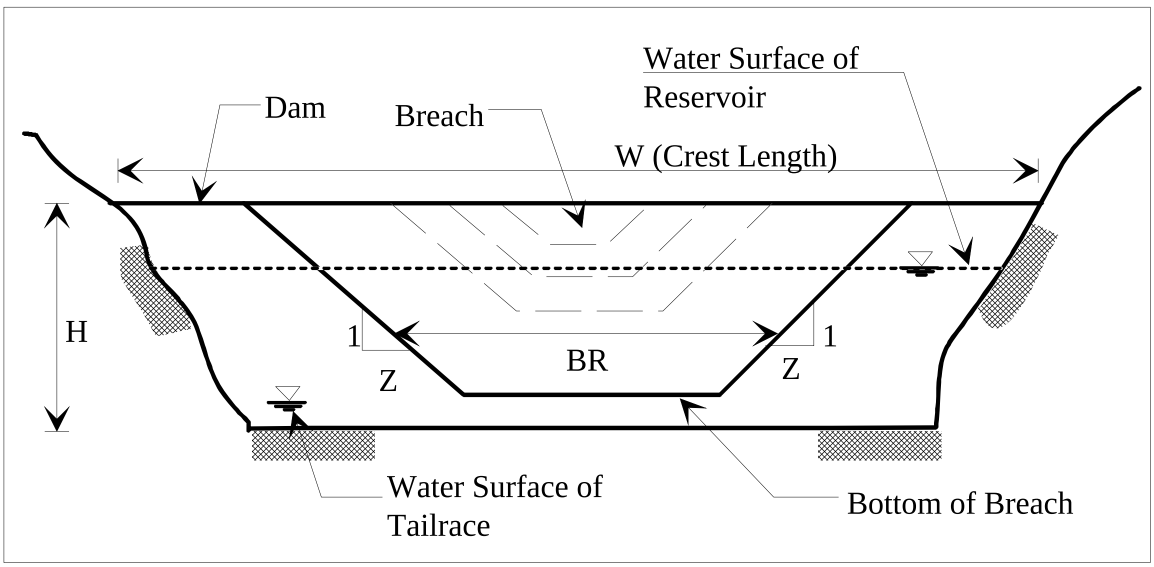


Figure 9.3 Definition sketch of the breach parameters.

Roughness Coefficients - Manning's "n" which represents the roughness of the river channel is the most indeterminate variable in dam break modeling. Calibrated values from high-water marks cannot really be used to represent those expected under a dam failure flood. Published data such as those from the U.S.G.S. can only be used to approximate the expected value from the hypothetical flooding. Therefore, it is necessary that relatively reasonable values be assumed or considered before a flood plain analysis is started. In most cases, these assumed values are varied through the modeling effort in order to resolve non-convergence problems with DAMBRK.

Table 9.4 Recommended Values of Manning's n
(US Dept. of Transportation, 1980)

Channel Type	n Values
1. Fairly regular section	
a. Some grass and weeds, little or no brush	0.30-0.035
b. Dense growth of weeds, depth of flow materially greater than weed height	0.35-0.05
c. Some weeds, light brush on banks	0.35-0.05
d. Some weeds, heavy brush on banks	0.05-0.07
e. Some weeds, dense willows on banks	0.06-0.08
f. For trees within channel, with branches submerged at high stage, increase all above values by	0.01-0.02
2. Irregular sections, with pools, slight channel meander; increase values given above about	0.01-0.02
3. Mountain streams, no vegetation in channel, banks usually steep, trees and brush along banks submerged at high stage:	
a. Bottom of gravel, cobbles, and few boulders	0.04-0.05
b. Bottom of cobbles, with large boulders	0.05-0.07

Routing - Generally the flood wave from a hypothetical dam break flood should be routed downstream to the point where the failure will no longer constitute a threat to human life or property. The results of the routing should be plotted on inundation maps with the dam break flood wave travel time and flood depths indicated at critical downstream locations.

9.3.2 Levee Failure

The guidance for expert generated inundation due to levee failure is essentially the same as the guidance for dam failures. The NWS DAMBRK software is used to determine the flooding due to levee failure. However, in the case of levee failure the analyst should consider multiple locations for levee failure based on a consideration of the locations where the levee may be most vulnerable and where the impact of flooding in the study area would be greatest.

9.3.3 Tsunami

The most detailed work on inundation map preparation from tsunami has been conducted for Hawaii, though sophisticated analyses have also been conducted for areas of the West Coast. Therefore, most guidelines refer to the work in this state. However, it should be noted that even though the following guidelines have been applied to Hawaii, the same procedures and assumptions could be adapted to other coastlines of the country that would be subject to tsunami flooding.

Tsunami inundation maps that have been produced are based on computer programs that are considered state-of-the-art. However, these programs are still short of the accuracy attainable by hurricane and storm-surge simulation programs. A two-dimensional model is recommended for modeling of tsunami for inundation studies. The available two-dimensional models solve the non-linear shallow water long wave equation using different methods of finite difference solution. A complete description of the available and verified models in the United Sates is provided in Bernard and Gonzalez, 1994. Numeric models are used to make scenario specific tsunami assessments. Inputs required for this assessment include detailed information on the location of earthquake and fault movement that is expected to occur on the ocean floor. In addition, information is needed regarding the bathymetry of the ocean floor, shoreline geometry, topographic data and tide information. Good quality bathymetric and topographic data are essential for accurate inundation model results.

9.3.4 Seiche

A detailed assessment is performed to estimate the seiche hazard at natural and man-made bodies of water. Input to this assessment includes the length, width and depth of each body of water and rim topographic and geologic information required to assess landslide potential and wave run-up. The length and width of the lake or reservoir correspond to the average dimensions of the body of water where wave generation is evaluated. The user may have to consider a number of different wave geometries to determine the critical dimensions that generate the largest estimated wave height. At a minimum, geologic maps of the lake or reservoir rim or landslide potential maps should be obtained. In addition, for earthquakes that occur on faults along or within bodies of water, the location of the event and the magnitude of vertical fault displacement is required.

A simple calculation is performed to determine the maximum wave height that would be generated by an earthquake. The following relationship can be used to estimate the peak wave height.

$$H = \sqrt{\frac{A}{L(\pi f)^2}} \tag{9-1}$$

where:

H = peak wave height (cm)
A = peak ground acceleration (in g's)
f = frequency of the lake (Hz)
L = Wavelength = $5.12 / f^2$

The above approach is a simplified method to estimate the peak wave height of a seiche generated by seismic motion at the lake. As part of this assessment the analyst must consider the occurrence of waves along alternative axes in the lake. Since the natural period of the lake is based on its shape, the period will be different on different axes.

Oscillations of water bodies above and below their mean level have a natural period depending upon the physical features of the water body. A disturbing force with the same period of oscillation as the lake or pool builds up the seiche to the point where the energy dissipated by friction equals the rate of application of energy. When the force causing the displacement ceases or changes in intensity, a series of pulsations follow at the natural frequency until damped by frictional forces. Standing waves of large amplitude are likely to be generated when the causative forces which sets the water basin in motion is periodic in character, especially if the period of these forces is the same as, or is in resonance with, the natural or free oscillation period of the basin.

The period of the seiche is dependent on the geometry of the basin. This period can be estimated with Merian's equation.

$$T_n = \frac{2l_b}{n\sqrt{gd}} \tag{9-2}$$

where:

T_n = period in seconds
l_b = length of the basin
n = number of nodes 1,2,3,...
g = gravitational acceleration
d = depth of water

For the fundamental and maximum period (T_n for n=1),

$$T_1 = \frac{2l_b}{\sqrt{gd}} \tag{9-3}$$

However, the preceding equation is based on the assumption of uniform and constant cross-section in the basin. In a basin of irregular section, the period is given by integrating equation 9-4. The frequency of the basin is the reciprocal of the period.

$$T = 2\int_0^{l_b} \frac{dx}{\sqrt{gd}} \tag{9-4}$$

where dx = finite increment of l_b.

9.4 Inundation References

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Chapter 10
Induced Damage Models - Fire Following Earthquake

10.1 Introduction

Fires following earthquakes can cause severe losses. These losses can sometimes outweigh the total losses from the direct damage caused by the earthquake, such as collapse of buildings and disruption of lifelines. Many factors affect the severity of the fires following an earthquake, including but not limited to: ignition sources, types and density of fuel, weather conditions, functionality of water systems, and the ability of fire fighters to suppress the fires.

It should be recognized that a complete fire following earthquake model requires extensive input with respect to the level of readiness of local fire departments and the types and availability (functionality) of water systems. To reduce the input requirements and to account for simplifications in the lifeline module, the fire following earthquake model presented in this report is also simplified. In addition, while building upon past efforts, the model is still to be considered a technology which is in its maturing process. With better understanding of fires that will be garnered after future earthquakes, there will undoubtedly be room for improvement in our forecasting capability. The methodology, highlighting the Fire Following Earthquake component, is shown in Flowchart 10.1

10.1.1 Scope

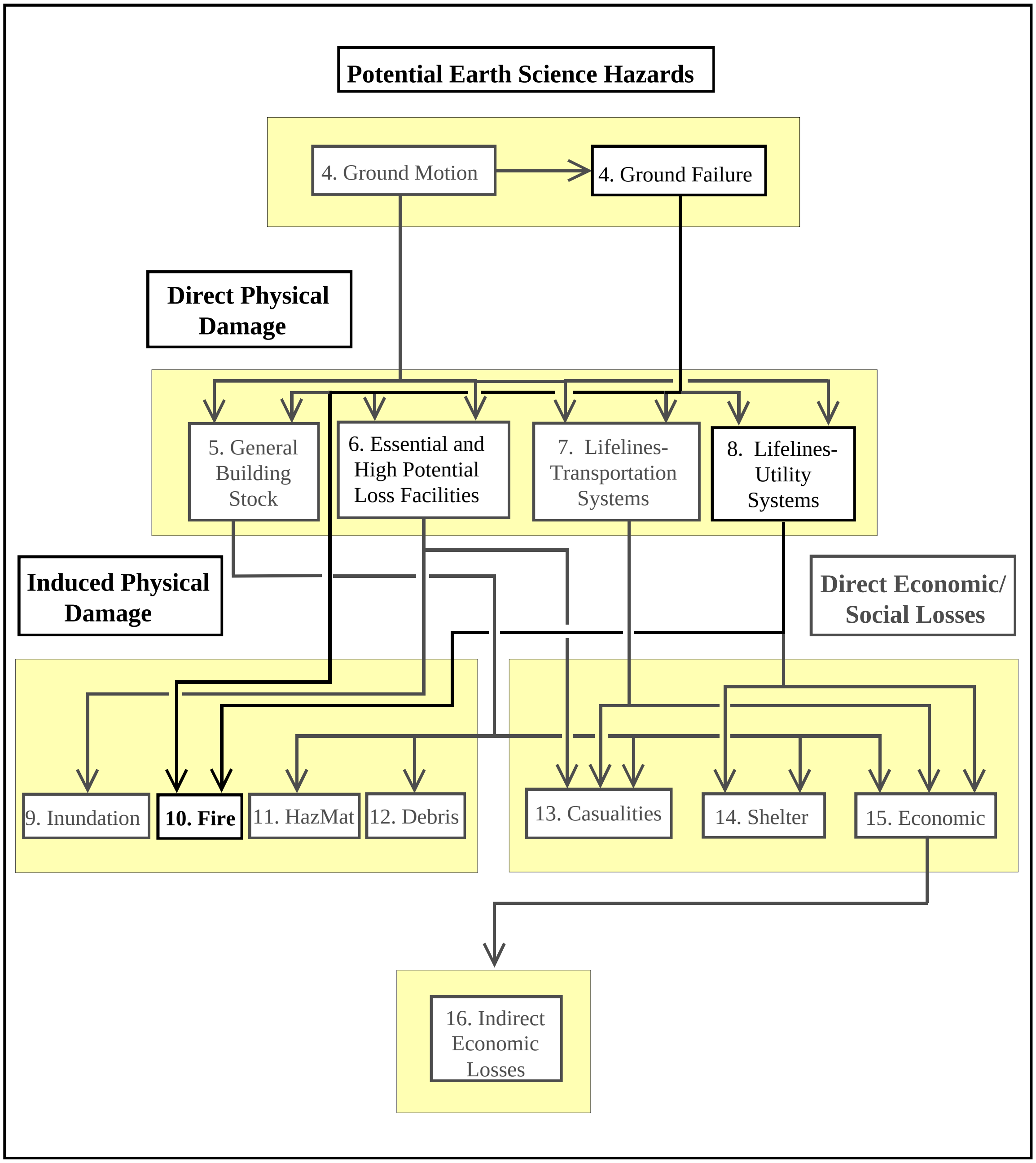
A complete fire following earthquake (FFE) model encompasses the three phases of a fire:

- ignition
- spread
- suppression

This methodology provides the user with the following estimates:

- Number of ignitions
- Total burned area
- Population exposed to the fires
- Building value consumed by the fire

Using Default and User-Supplied Data Analysis information will provide an estimate of the magnitude of the FFE problem, that could be used to plan for and estimate demands on local fire fighting resources.



Flowchart 10.1: Fire Following Earthquake Component Relationship to other Modules in the Earthquake Loss Estimation Methodology

10.1.2 Form of Damage Estimates

The FFE methodology provides the following:

- an estimate of the number of serious fire ignitions that require fire department response after a scenario earthquake
- an estimate of the total burned area
- an estimate of the population and building exposure affected by the fire

By applying the FFE module for several scenario earthquakes, representing different potential earthquakes for the study area, with different recurrence intervals, the user can examine the efficacy of certain pre-earthquake actions that can be used to mitigate the potential losses from fires in future earthquakes. For example, the user could study the effect of building more fire stations; adding more fire apparatus; improving immediate post-earthquake response to detect fires and suppress fires before they spread or seismically upgrading the water system. Since all these activities cost money, the user could study which combination of activities is most effective for their communities.

10.1.3 Input Requirements

This section describes the inputs required and output provided by the FFE module.

Input for Analysis:

Provided as general building stock inventory data:

- Square footage of residential single family dwellings (SFD)
- Square footage of residential non-SFD
- Square footage of commercial buildings
- Square footage of industrial buildings

Provided as essential facility inventory data:

- Number of fire stations
- Number of engines at each fire stations
- Geographical location of each station

Provided by the PESH module:

- PGA

Analysis options input by the user:

- Wind speed
- Wind direction
- Speed of the fire engine truck (after earthquake)
- Number of Simulations
- Maximum Simulation Time
- Simulation Time Increment

Multiple estimates for the same scenario earthquake are calculated by simulating fire following earthquakes several times. Hence, the user needs to provide the number of simulations that should be performed in order to come up with average estimates from independent simulations. It is suggested that the user try 6 to 10 simulations. The maximum time after the earthquake for which the simulation should be performed and the time increment for each simulation are also user inputs. For example, a reasonable maximum time could be 10,000 minutes when all the fires could possibly be suppressed. It is suggested that a time increment of 1 to 15 minutes be provided for sufficiently accurate simulations.

10.2 Description of Methodology

10.2.1 Ignition

The first step in evaluating the potential losses due to fires following earthquake is to estimate the number of fires that actually occur after the earthquake. The ignition model is based on the number of serious FFEs that have occurred after past earthquakes in the United States.

The term "ignition" refers to each individual fire that starts (ignites) after an earthquake that ultimately requires fire department response to suppress. Thus, a fire that starts after an earthquake but which is put out by the occupants of the building without fire department response is not considered an ignition for purposes of this model. Fires that are put out by building occupants are usually those discovered very early and are put out before they can do substantial damage. These ignitions do not lead to significant losses.
Ignitions are calculated on the basis of an ‘ignition rate’, which is the frequency of ignitions normalized by a measure of the potential source of ignitions. For Hazus, the ignition rate is frequency of ignitions per million square feet of total building floor area per district considered.

Ignition rates for use in Hazus were determined according to an empirical statistical analysis, in the following steps.

R10.2.1.1 Ignition Data Sources

Initially, all 20th century earthquakes, U.S. as well as foreign, were considered as potential data sources for post-earthquake ignitions. Several criteria were used to focus on events for analysis:

- Only events that had sustained ignitions per the definition of an ignition being an *individual fire that starts (ignites) after an earthquake that ultimately requires fire department response to suppress* were considered.
- Only U.S. data was employed. Use of non-U.S. data was considered early in the study, but was rejected due to most non-U.S. data being derived from Japan, with homogeneity being problematic. While Japan is an advanced technological society like the U.S., with comparable safety and other standards, the residential building construction in Japan differs significantly from that in the U.S. A simple example suffices: the 1994 M_w 6.7 Northridge earthquake in southern California affected a population of perhaps 3 million people within the MMI VI isoseismal,

had relatively few collapsed buildings, approximately 110 ignitions and 67 people killed. The 1995 Mw 6.9 Hanshin Awaji (Kobe) earthquake in Japan comparably affected perhaps 1.5 million people, had thousands of collapsed buildings (majority residential), approximately 110 ignitions and 6,000 people killed (Scawthorn 1996). Beyond the real issues of comparability of data, merging non-U.S. with U.S. data would raise innumerable questions that Hazus management would be called to respond to for the foreseeable future.

- Post-1970 data was employed. Use of earlier events was considered early in the study – previous analyses including that for Hazus have used data as far back as 1906, and there are some arguments for still doing this. However, building standards, household appliance and industrial safety standards and the nature of the urban region (post-industrial) argue for only using more recent data. Because the 1971 San Fernando event was considered still relevant, 1970 was selected as the cut-off.

Using these criteria, seven events were identified with significant data and adequate documentation:

- 1971 San Fernando
- 1983 Coalinga
- 1984 Morgan Hill
- 1986 N. Palm Springs
- 1987 Whittier Narrows
- 1989 Loma Prieta
- 1994 Northridge

The ignition data so identified total 238 and are summarized in Table 10.1, and their distribution is shown Figure 10.1. Ignition data employed in the previous Hazus model totaled 30.

Table 10.1 Summary Count of Ignition Data

Earthquake	# ignitions in data set	Source of Data
1971 San Fernando	91	Unpublished data
1983 Coalinga	3	(Scawthorn 1984)
1984 Morgan Hill	6	(Scawthorn 1985)
1986 N. Palm Springs	1	(EERI 1986)
1987 Whittier Narrows	20	(Wiggins 1988)
1989 Loma Prieta	36	(Mohammadi et al. 1992; Scawthorn 1991)
1994 Northridge	81	(Scawthorn et al. 1997)
Total # of ignitions	**238**	

R10.2.1.2 Ground Motions

For correlating ignition data with ground motions, the USGS ShakeMap archive[i] provided consistent high quality data sets for these seven events, in terms of Modified Mercalli Intensity (MMI), Peak Ground Acceleration (PGA), Peak Ground Velocity (PGV) and Response Spectral Acceleration (for 0.3sec, $Sa_{.03}$). Note that the ShakeMaps include local soil conditions and site effects, within the limits of the relevant databases.

[i] http://earthquake.usgs.gov/eqcenter/shakemap/list.php?y=2006. Ground motions in ShakeMap are determined using Wald et al (1999).

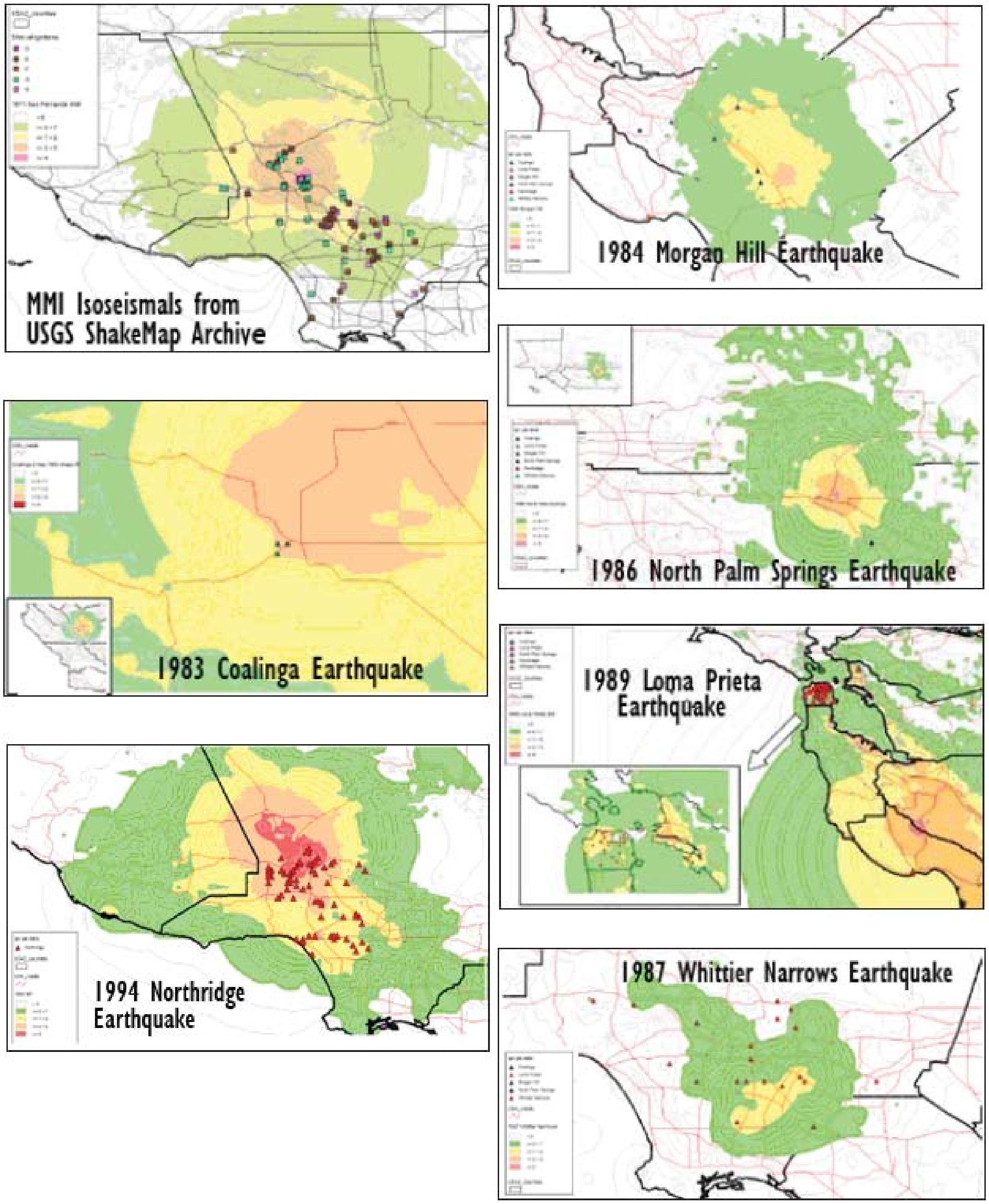


Figure 10.1 Distribution of Ignitions vs. MMI in Seven Selected Earthquakes

R10.2.1.3 Analysis

The specific approach employed for post-earthquake ignitons was to overlay the ignition data discussed above on a relatively detailed mesh of the areas affected in each event, in order to determine ignition rates normalized by some measure of the earthquake intensity and exposure of potential ignition sources. Where previous studies had used 'city' sized data points, meshes considered for this study were regular grids (e.g., 1 km. square), census tracts, fire battalion districts and postal codes. After some preliminary analysis, 2000 census tracts were chosen as the level of granularity for the analysis. For such a fine mesh, only a few tracts had more than one ignition. For the seven event data sets, use of census tracts resulted in a large number of tracts. Two criteria were employed to identify a more meaningful set of tracts:

- **Intensity**: only tracts experiencing 0.13g (MMI VI) or greater were employed. Previous analyses has shown that at MMI VI or less ignition rates are negligible – inclusion of tracts with less than MMI VI shaking would result in a weak ‘signal-noise’ ratio for the analysis. Culling tracts with MMI VI or less resulted in loss of a few ignition points.
- **Population Density**: only census tracts with population density of 3,000 persons per square kilometer or greater were employed in the analysis. The reason for this is that tracts with sparser population will again have a weak ‘signal-noise’ ratio and, more importantly, the fire following earthquake problem is relatively negligible in such sparsely populated tracts, as fire spread is typically nil. An additional consideration is that only in moderately or greater populated areas are there sufficient concentrations of housing and infrastructure to result in significant ignition rates. For reference:
    - Los Angeles - the average population density of the entire City of Los Angeles is 3,168 per sq. km. (total 2006 population 3,849,378 and total area 1,290.6 sq. km.), with some census tracts having densities of 18,000 per sq. km.
    - Berkeley (Alameda County) has a population density of 3,792
    - City of San Francisco as a population density of 6,607 per sq. km, with some tracts over 20,000.

In effect, these two criteria (PGA $\geq$ 0.13G, population density $\geq$ 3,000 per sq. km.) restricted the analysis to urban settings where fire following earthquake is a concern. Using these two criteria reduced the number of census tracts for the seven events to 1,435. For this group of census tracts, the frequency distribution of PGA is shown in Figure 10.2. Note that virtually 100% of the data set experienced ground motions greater than 0.2g. Since some of the census tracts had experienced more than one ignition in an earthquake, the resulting number of census tracts with ignition data is 155, or about 10.8% of the data set. That is, 1,380 tracts (89.2%) are ‘zero-ignition’ points.

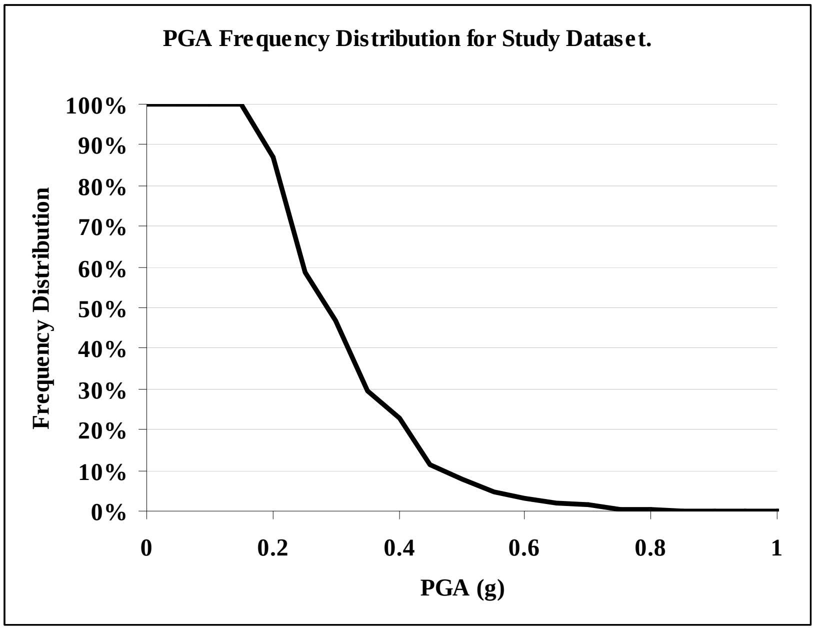


Figure 10.2 PGA Frequency Distribution for Study Data Set (n=1,435)

For each census tract in the resulting data set, the analysis normalized the number of ignitions by several measures, including (a) building total floor area, for all buildings, and for various combinations of model building types (e.g., total floor area for only wood framed buildings; total floor area for wood framed and unreinforced masonry buildings, etc); (b) similarly, weighted averages of various combinations of total floor area of damaged buildings; and (c) other socio-economic measures, such as population, and built-upness (total floor area density). Each of these measures were regressed against the several measures of ground motion (MMI, PGA, PGV, $Sa_{.03}$), for a number of functional forms – linear, polynomial, semi-log, and power law. The criterion for best fit was correlation coefficient.

While a number of combinations of covariates were examined, the best result was a polynomial equation relating ignitions per million sq. ft. of total floor area, with PGA. The specific equation is:

$$\mathbf{Ign./TFA = 0.581895\ (PGA)^2 - 0.029444\ (PGA)} \qquad R^2 = 0.084 \qquad (10\text{-}1)$$

where Ign/TFA is the mean number of ignitions per million sq. ft. of building total floor area in the area of interest (e.g., census tract, although the equation is applicable to any area). Equation R10.1 and Ign/TFA data plotted versus PGA are shown in Figure 10.3. Analysis shows the distribution of the logarithm of the data-regression residuals may be approximated as a normal distribution with mean zero and standard deviation of 0.12.

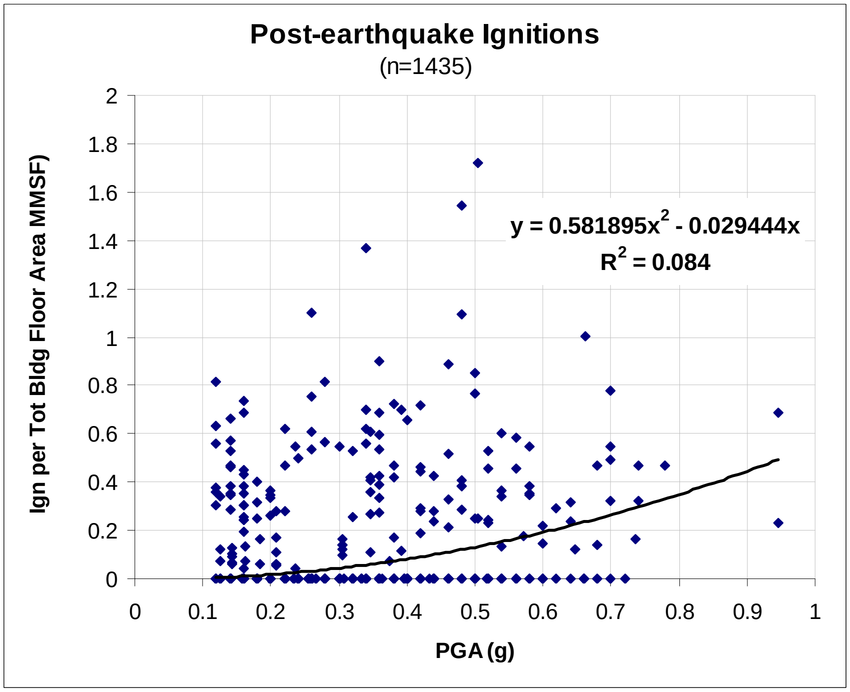


Figure 10.3 Ignition Rate Data and Regression as Function of PGA (n=1,435)

R10.2.1.4 Temporal distribution of Ignitions

The above equation for ignition rates is empirical, and includes fires both starting immediately after the earthquake and starting some time after the earthquake. Empirical analysis indicates about 20% of the ignitions will have occurred within the first hour, about half will occurred within 6 hours, and almost all by the end of the first day. Note that while fire departments typically have response goals of only several minutes, the time on-scene for a structural fire is typically several hours, so it can be seen that departments will be occupied with the first wave of fires as others are continuing to occur. See (SPA, 2009) for further details.

10.2.2 Spread

The second step in performing the FFE analysis is to estimate the spread of the initial fire ignition. The following description of fire spread in urban areas is based on a model developed by Hamada (1975). Hamada developed a model for fire spreading for urban Japan. His model is described as follows:

$$N_{tV} = \frac{1.5\delta}{a^2} * K_s * \left(K_d + K_u\right) \tag{10-2}$$

where:

N_{tV} = Number of structures fully burned

t = time, in minutes after initial ignition

V = wind velocity, in meters per second
δ = "Built-upness" factor, dimensionless, described below
a = average structure plan dimension, in meters
d = average building separation, in meters
K_s = half the width of fire from flank to flank, in meters
K_d = length of fire in downwind direction, from the initial ignition location, in meters
K_u = length of fire in upwind (rear) direction, from the initial ignition location, in meters

$$\delta = \frac{\sum_{i=1}^{n} a_i^2}{\text{Tract Area}} \tag{10-3a}$$

where:
a_i = plan dimension of building i
n = number of structures

$$K_d = \frac{(a+d)}{T_d} * t \tag{10-3b}$$

$$K_s = \left(\frac{a}{2}+d\right) + \frac{(a+d)}{T_s}\left(t - T_s\right) \quad ; \quad K_s \geq 0 \tag{10-3c}$$

$$K_u = \left(\frac{a}{2}+d\right) + \frac{(a+d)}{T_u}\left(t - T_u\right) \quad ; \quad K_u \geq 0 \tag{10-3d}$$

$$T_d = \frac{1}{1.6\left(1+0.1V+0.007V^2\right)}\left[\left(1-f_b\right)\left(3+0.375a+\frac{8d}{25+2.5V}\right) + f_b\left(5+0.625a+\frac{16d}{25+2.5V}\right)\right] \tag{10-3e}$$

$$T_s = \frac{1}{1+0.005V^2}\left[\left(1-f_b\right)\left(3+0.375a+\frac{8d}{5+0.25V}\right) + f_b\left(5+0.625a+\frac{16d}{5+0.25V}\right)\right]$$

(10-3f)

$$T_u = \frac{1}{1+0.002V^2}\left[\left(1-f_b\right)\left(3+0.375a+\frac{8d}{5+0.2V}\right) + f_b\left(5+0.625a+\frac{16d}{5+0.2V}\right)\right]$$

(10-3g)

where:

$$f_b = \frac{\text{Number of fire resistant buildings}}{\text{All buildings}}$$

A discussion of the Hamada model follows.

- It is assumed that an urban area is represented by a series of equal square (plan area) structures, with equal spacing between structures. The plan dimension of the average structure is denoted "a", and hence the plan area is a^2.

- It is assumed that the spaces between structures in a subdivision can be represented by an average separation distance, d. For purposes of this model, the separation distance represents the typical distance between structures within a single block. This distance accounts for side yards, backyards and front yards, but does not include streets and sidewalks.

- The "built-upness", or building density ratio δ is defined by equation 10-3a. To put this building density ratio in context, a value of 0.35 represents a densely built area, and a value of 0.10 represents an area which is not very densely built.

- Figure 10.4 shows the fire spread in terms of ovals, which is the usual case of fires burning through an evenly distributed fuel load, with constant wind velocity. In the actual urban conflagrations, fires exhibit this trend initially, but the final shape of the fire spread differs, as different fuel loads are experienced, as wind shifts, and as different fire suppression actions take place. The fire burn area is approximated as the product of the downwind fire spread plus the upwind fire spread (K_d + K_u) times the width of the fire spread ($2K_s$).

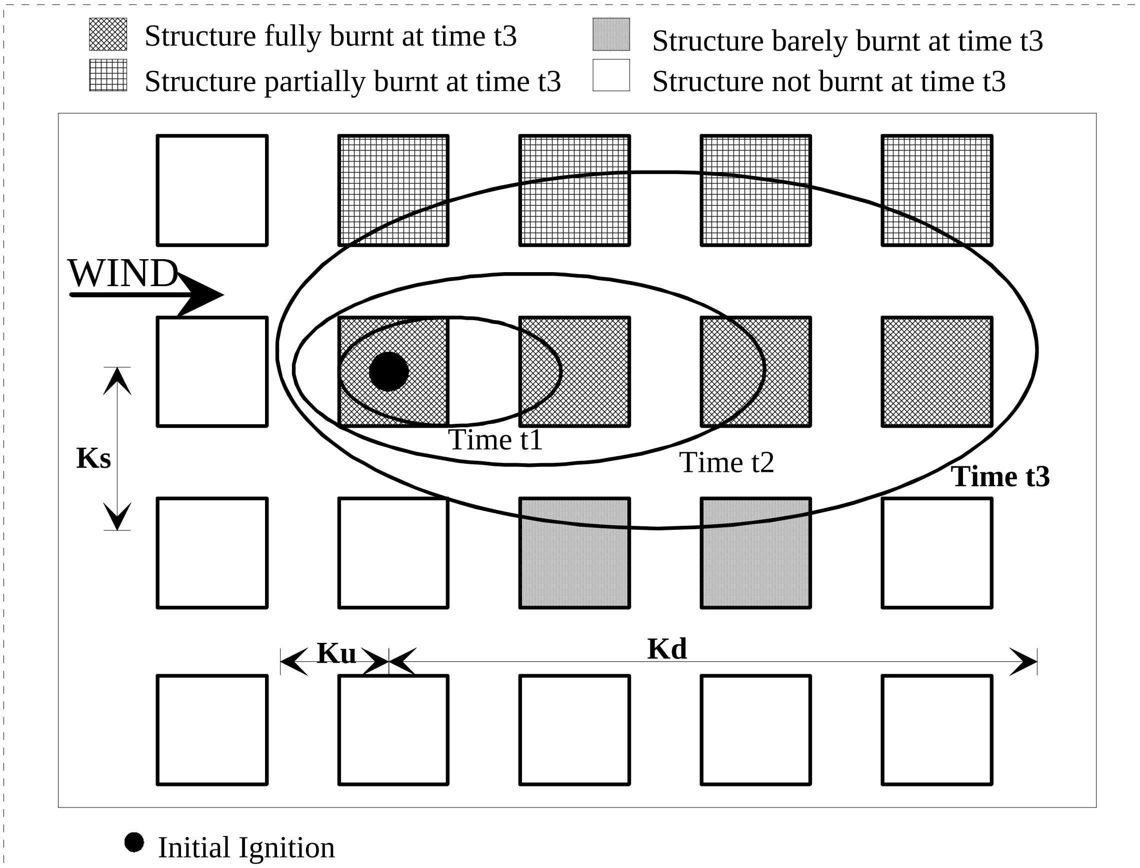


Figure 10.4 Fire Spread Process.

- The fire spread model accounts for the speed of advance of the fire considering the following variables:
  - **Direction of spread**. The speed of advance of the fire is highest in the downwind direction, slower in the side wind direction, and slowest in the upwind direction.
  - **Wind velocity**. The speed of advance of the fire increases as the square of the wind velocity.
  - **Fire resistance of structures**. The speed of advance through wood structures is about twice the speed of advance through fire resistant structures.

It should be noted that the Hamada model results in different fire spreading rates in the downwind, sidewind, and upwind directions even for zero wind speed. To correct this problem, a linear interpolation function is introduced which forces the fire spreading rates to be equal in all directions as the wind speed approaches zero. For wind speeds less than 10 m/sec, the adjusted fire spreading rates (K_d', K_u' and K_s') are given as follows:

$$K_d^{'} = K_d\left(\frac{V}{10}\right) + \sqrt{\left(\frac{K_d + K_u}{2}\right)K_s}\left(1 - \frac{V}{10}\right) \tag{10-4a}$$

$$K_u^{'} = K_u\left(\frac{V}{10}\right) + \sqrt{\left(\frac{K_d + K_u}{2}\right)K_s}\left(1 - \frac{V}{10}\right) \tag{10-4b}$$

$$K_s^{'} = K_s\left(\frac{V}{10}\right) + \sqrt{\left(\frac{K_d + K_u}{2}\right)K_s}\left(1 - \frac{V}{10}\right) \tag{10-4c}$$

10.2.3 Suppression

The term suppression is defined as all the work of extinguishing a fire, beginning with its discovery. The steps in the suppression activity are defined as follows:

- **Discovery Time**. Elapsed time from the start of the fire until the time of the first discovery which results directly in subsequent suppression action.
- **Report Time**. Elapsed time from discovery of a fire until it is reported to a fire agency that will respond with personnel, supplies and equipment to the fire.
- **Arrival Time**. Elapsed time from the report time until the beginning of effective work on a fire.
- **Control Time**. Elapsed time from the beginning of effective work on a fire to when the fire is controlled.
- **Mop-up Time**. Elapsed time from completion of the controlling process until enough mop-up has been done to ensure that the fire will not break out and the structure is safe to re-occupy.

10.2.3.1 Discovery Time

The time to discover a fire is usually on the order of a few minutes if anyone is present to observe the fire. In modern urban areas, many structures have smoke detectors, and these will alert occupants or perhaps people nearby the structure that a fire has ignited. The following discovery model is used:

- 85 percent of structures are occupied at the time of the earthquake. In these structures, fires are discovered randomly between 0 and 5 minutes.
- 15 percent of structures are not occupied at the time of the earthquake. In these structures, fires are discovered randomly between 3 and 10 minutes.

10.2.3.2 Report Time

The time to report a fire is usually less than one minute under non-earthquake conditions. Most people report a fire directly to the fire department or call 911. The 911 dispatchers determines the degree of the emergency and notify the fire department.

After an earthquake, this usual method to report fires will be hampered, either due to phone system overload (inability to get a dial tone) or due to physical damage to various parts of the phone system. In theory, the fire model could account for the various levels of phone system damage from outputs from the communications module. However, for simplification the report time aspects are based on the following methods.

Five different methods are considered in determining how the fire will actually be reported to the fire department after an earthquake.

- **Cellular phone**: The model assumes that 15 percent of all fires can be reported by cellular phone taking 1 minute.
- **Regular phone**: The model assumes that 25 percent of all fires can be reported by regular phone taking 1 minute; 50 percent of all fires can be reported by regular phone, taking anywhere from 1 to 5 minutes; and 25 percent of all fires cannot be reported by regular phone.
- **Citizen alert**: In all fires, one option to report fires is for the resident to walk or drive to the nearest fire station and report the fire. This method of reporting is available for all fire ignitions. The time to report such a fire is anywhere from 1 to 11 minutes.
- **Roving Fire Vehicle**: A fire department practice for fire response after earthquakes is to immediately get fire apparatus onto the streets, looking for fires. The model assumes that a roving vehicle can detect a fire somewhere between 3 and 14 minutes after the earthquake.
- **Aircraft**: In many post-earthquake responses, helicopters and other aircraft will be flying over the affected areas. Often by the time a fire is spotted at height, it has already grown to significant proportions. The model assumes that fires can be detected by aircraft anywhere from 6 minutes to 20 minutes after the earthquake.

The model considers all five methods to report fires. The method which results in the earliest detection is the one which is used in the subsequent analysis.

10.2.3.3 Arrival Time

The arrival time is the time it takes after the fire is reported for the first fire suppression personnel and apparatus to arrive at a fire ignition. Under non-earthquake conditions, fire engines respond to fires by driving at about 30 miles per hour on average. After an earthquake, it is expected that fire engines will have a somewhat more difficult time in arriving at a fire due to damage to the road network, debris in the streets due to fallen power poles or damaged structures, traffic jam caused by signal outages, and the like.

The model accounts for this slowdown in arrival time as follows:

- If the fire was detected by a roving fire engine, arrival time is 0 minutes (the engine is already at the fire).
- If the fire is called in or reported by citizens, the time for the first engine from a local fire department to arrive at the fire is between 2 and 12 minutes. (Under non-earthquake conditions, arrival time is usually about 1 - 6 minutes, so the model assumes that the fire engines drive at 50 percent of normal speed).

10.2.3.4 Control Time

The time and resources needed to control the fire will depend upon the status of the fire at first arrival of the first fire engine. The model accounts for different control times considering the status of the fire. Since the status of a fire can vary over time, the model continues to check fire status every minute.

10.2.3.4.1 Room and Contents Fires

If the total time from ignition to arrival is short, then the fire may be still a "room and contents" fire. These fires are small, and most fire engines carry enough water in the truck to control them. (Typical water carried in a pumper truck is 500 gallons to 1000 gallons). If this is the case, the model assumes that the first responding fire engine can control the fire. The engine is held at the location of the fire for 10 minutes. Thereafter, the engine is released for response to other fires that may be ongoing.

10.2.3.4.2 Structure Fires - Engines Needed

If the fire has spread to beyond a room and contents fire, then suppression activities require two resources: an adequate number of fire apparatus (engine trucks, ladder trucks, hose trucks) and personnel, and an adequate amount of water.

Most fire apparatus today are engine trucks, and the model does not differentiate between the capabilities of a ladder truck and an engine truck. (The user should input to the model the sum of fire department apparatus which can pump water at a rate of about 1,000 gpm to 2,000 gpm. Hose tenders without pumps, search and rescue trucks, and automobiles are not counted as available apparatus in the model).

The model determines the number of required trucks as follows:

- Single Family Residential Fires. Figure 10.5 shows the number of fire trucks needed to suppress a fire, versus the number of structures already burned.
- Other Fires. Figure 10.6 shows the number of fire trucks needed to suppress a fire, versus the number of structures already burned, for the case when the original ignition was at a structure other than a single family building. These ignitions include fires at apartment, commercial, wholesale and industrial structures. From Figure 10.6, it is shown that a minimum of two trucks are needed if the burnt structures range from zero to four. Since only one truck is sent to each fire, this leads to all fires becoming a conflagration, regardless of size. A modification is introduced by modifying the requirement to:

    - One truck is needed if the burnt structures are less than 2.
    - Two trucks are needed if the burnt structures are between 2 and 4.

This modification will reduce the total burnt area since all fires close to the fire stations will be controlled and putout by only one engine.

10.2.3.4.3 Structure Fires - Water Needed

Except in the case of room and content fires, urban fire suppression usually requires large quantities of water in order to gain control. (The issue of firebreaks in urban areas is described later). The amount of water needed is usually expressed in two terms:

- **Required Flow**: This is the amount of water needed to fight a fire from one or more fire hydrants, usually expressed in gallons per minute, gpm.
- **Required duration**: This is the length of time the fire flow is needed, in hours (or minutes).

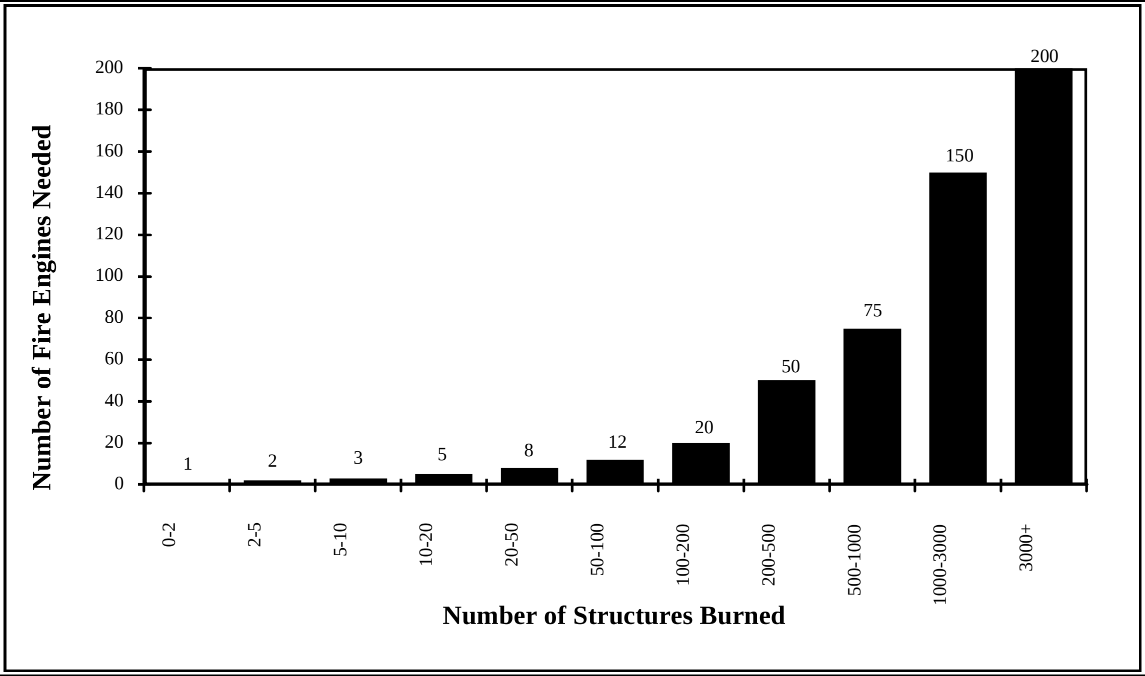


Figure 10.5 Ignitions That Start in Single Family Structures.

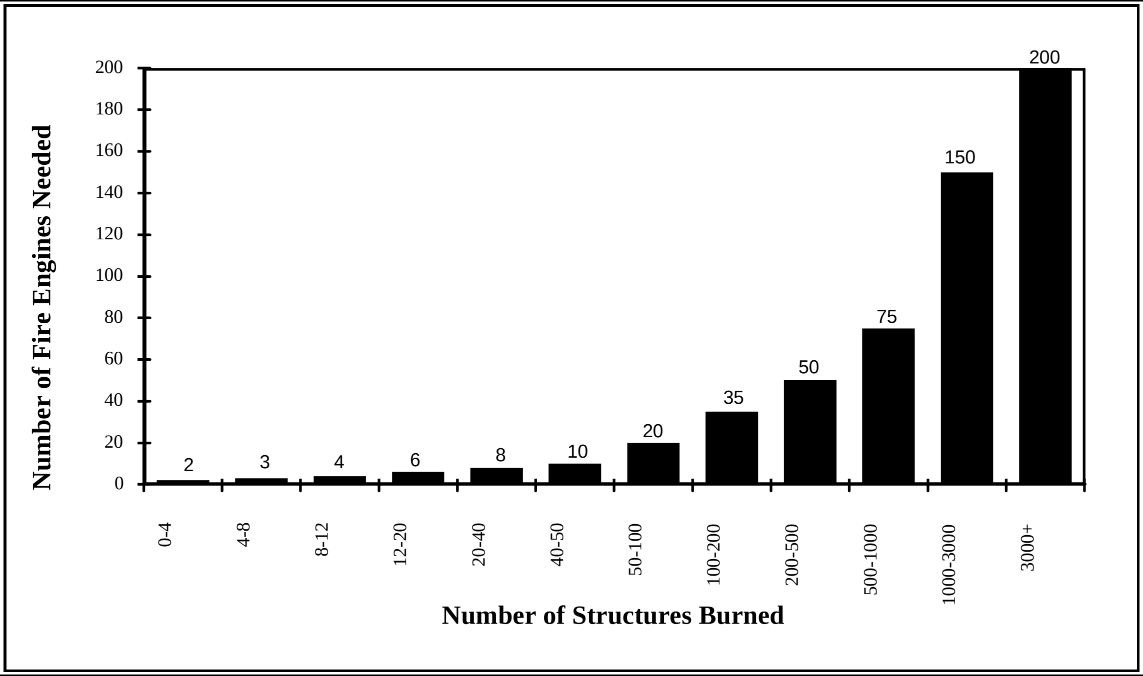


Figure 10.6 Ignitions That Start in Non-Single Family Structures.

A term often used in describing water needs is pressure. In the usual fire fighting terminology, the fire flows are required at the hydrant outlet at a minimum of 20 psi residual pressure while the hydrant is flowing.

Most cities use a water distribution system that delivers water for customer needs (drinking, sanitary, and other uses) and water for fire flow needs through a single set of pipes. Water pressures are usually kept in the mains at around 40 psi - 60 psi to meet normal customer needs. When a hydrant is opened, flows through the water mains increase. In areas of the city where mains are not highly interconnected (such as in hillside communities) or where mains have small diameters (2", 4" and some 6" pipes), the high velocities of water needed to deliver the water to the fire hydrant cause significant pressure drops. If the water pressure drops below about 20 psi, then fire engines have a difficult time drafting the water out of the hydrant.

The water needed to fight a fire at any given time t (W_t in gallons), depends upon the extent of the fire. The following equations are used to calculate the water needed:

$$W_t = 1250\left(N_{tV}\right)^{0.4} \quad ; \quad 0 < N_{tV} \leq 3000 \qquad (10\text{-}5)$$

where N_{tV} = Number of structures burned at time t, at wind velocity V

Equation (10-5) is based upon the Uniform Fire Code (1991) for single structure fires (N_{tV} = 1) and modified for large conflagration fires.

For apartment fires, the amount of water needed is somewhat higher than the water needed for a single family residence, and is expressed in equations 10-6 and 10-7:

$$W_t = 1500(N_{tV})^{0.5} \quad ; \quad 0 < N_{tV} \leq 4 \tag{10-6}$$

or,

$$W_t = 3000 + 1250(N_{tV} - 4)^{0.4} \quad ; \quad 4 < N_{tV} \leq 3000 \tag{10-7}$$

For commercial, wholesale and industrial fires, the amount of water needed is higher than the water needed for a small apartment building, and is expressed in equations 10-8 and 10-9:

$$W_t = 2500(N_{tV})^{0.5} \quad ; \quad 0 < N_{tV} \leq 4 \tag{10-8}$$

or,

$$W_t = 5000 + 1250(N_{tV} - 4)^{0.4} \quad ; \quad 4 < N_{tV} \leq 3000 \tag{10-9}$$

For petroleum fires, the amount of water needed is higher than the water needed for other types of fires, and is expressed in equations 10-10 and 10-11:

$$W_t = 4000(N_{tV})^{0.5} \quad ; \quad 0 < N_{tV} \leq 4 \tag{10-10}$$

or,

$$W_t = 8000 + 1250(N_{tV} - 4)^{0.4} \quad ; \quad 4 < N_{tV} \leq 3000 \tag{10-11}$$

For all types of fires, the duration of flow is determined by equation 10-12:

$$D = 0.5 * (\text{engines needed})^{0.4} \tag{10-12}$$

where D = duration of flow needed, in hours
(engines needed) = taken from Figure 10.3 or 10.4

10.2.3.4.4 Engines Available

The number of fire apparatus (engines and ladders) available in the study area is supplied by the user as input to the model. The following information is needed:

- The number of pumper apparatus engines in every jurisdiction within the study area. The user must select the level of refinement of the jurisdiction within the study area. A jurisdiction can be set at either the fire station level, the battalion level, or the city level.
  - Jurisdictions can be set as a city if the city has population of about 400,000 people or less.

- Jurisdictions should be set as a battalion (or more refined) if the city has population greater than about 400,000.

- The number of pumper apparatus available from mutual aid, from jurisdictions outside the study area. Mutual aid jurisdictions can usually be set in terms of the number of pumper apparatus available within a county. The geographic extent of the earthquake should be considered to decide what proportion of mutual aid that can be normally counted on will be delivered.

The model tracks the order of detection of the fires. Fire engines will serve fires which have been discovered first and are nearest to the fire stations. An insufficient number of fire trucks will result in the fire spreading faster which will be addressed later.

10.2.3.4.5 Water Available

The water available to fight a fire depends upon the capacity of the water distribution system, taking into account the level of damage to the system. Parameters that determine the amount of water available in a cell to suppress fires include:

- Available water flow
- Duration of water flow for pumped water system

10.2.3.4.6 Fire Spread with Partially Effective Suppression

For each fire, at each time step of the analysis, the model checks to see what is the available flow for fire suppression activities and what number of fire trucks are at the scene of the fire. Based upon the size of the fire at that time, the model calculates the number of fire trucks needed and the amount of water normally needed to control the fire. From these values, two ratios are calculated:

$$R_{truck} = \frac{\text{trucks at fire}}{\text{trucks needed at fire}}, \qquad \text{but } R_{truck} \text{ should not exceed } 1.0$$

$$R_{water} = \frac{\text{available flow at fire}}{\text{flow needed}}, \qquad \text{but } R_{water} \text{ should not exceed } 1.0$$

where,

available flow = (reduction factor) * (typical discharge from hydrant) * (number of hydrants to fight fire)

The reduction factor is set to the serviceability index obtained from Chapter 8. The typical discharge from a hydrant is around 1750 gallons/min. Finally, the number of hydrants available at the scene of the fire is estimated as follows:

$$\text{No. of Hydrants} = 1.5 * (K_d+K_u)(2K_s)/(100*100)$$

Where K_d, K_u, and K_s are previously defined. Note that 100 is the average spacing in meters between fire hydrants (typically, the spacing is in the range 60 m to 150 m). The coefficient 1.5 reflects the assumption of 50% of additional fire hydrants from adjacent blocks or equivalent will be available to fight the fire.

Based on the calculated values of R_{truck} and R_{water}, the fire suppression effectiveness is:

$$P_{effective} = \left(R_{truck} * R_{water}\right)^{0.7} \geq 0.33R_{truck} \tag{10-13}$$

This equation reflects the following logic. If the available trucks and water are much less than required, then there is good chance that the fire will spread. Conversely, if most of the trucks and water needed are available, then the fire suppression effectiveness is much better.

Due to fire suppression, the rate of fire spread will be slowed down and the reduced rate will be

$$\text{Spread Rate} = \text{Spread}_{\text{non-suppressed}} \cdot \left(1 - P_{effective}^{0.7}\right) \tag{10-14}$$

The Spread Rate is the key variable used in determining the spread of the fire. Equations 10-13 and 10-14 together provide the prediction as to the effectiveness of partial fire suppression in stopping urban conflagration.

10.2.3.4.7 Fire Spread at Natural Fire Breaks

Fire breaks are one of the ways to stop fires from spreading. Fire breaks abound in an urban area and include streets, highways, parks, and lakes. The model accounts for fire breaks as follows:

- Fires can spread within a city block following equation 10-3 as modified by equation 10-14. The model keeps track of the spread.

- The average city block is assumed to have two rows of houses, and there are 15 houses down a single side of a block. The average length of a city block is taken as the average of the width and length of the block. If the user does not supply the average width of a city block street, including sidewalks, then the model will use default width of 25 meters.

- The model assumes that every fifth fire break is three times wider than the average city street fire break. These wide fire breaks account for the presence of wide boulevards, interstate highways, parks and lakes.

- If the fire spread just reaches a fire break, then there is a probability that the fire break will control the fire, even with no active suppression or partial suppression ongoing.

The probability of the fire jumping the fire break increases with the wind velocity, decreases with the width of the fire break, and decreases if there is active fire suppression as shown in Figure 10.7. Figure 10.7 is adapted from Scawthorn, 1987, and combined with judgment.

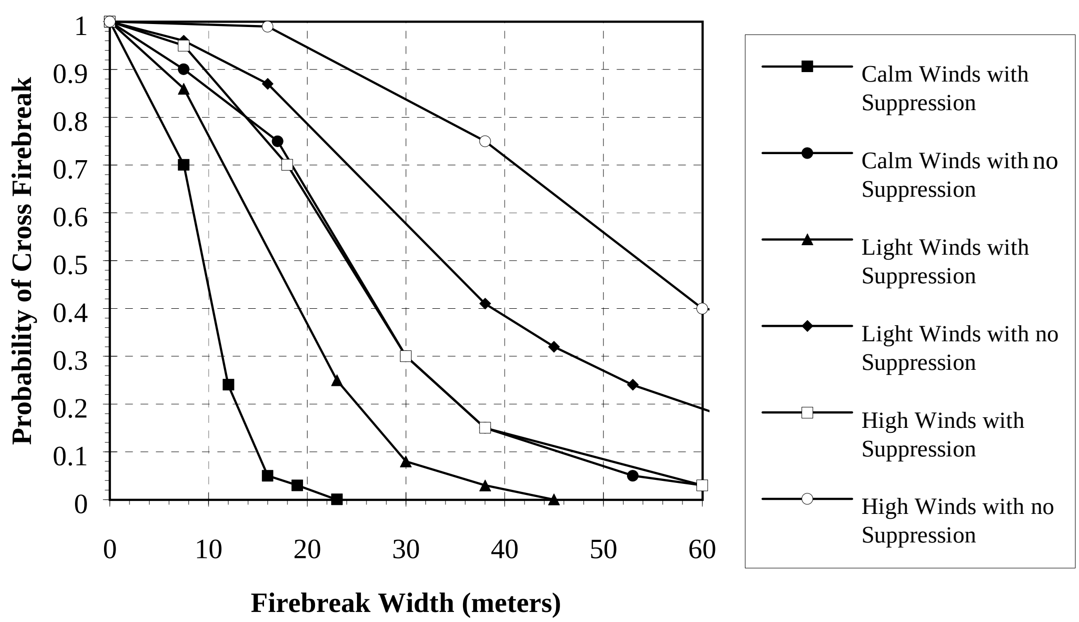


Figure 10.7 Probability of Crossing Firebreak.

10.3 Guidance for Expert-Generated Estimates

As described in Section 10.2, the FFE model makes several simplifying assumptions about the study area. Any or all of these assumptions can be relaxed, and the resulting FFE model will be more refined. The reader may adjust the model by relaxing the following assumptions:

- Analyze the actual water system, for each pressure zone. Many water systems are made up of dozens of pressure zones, many interdependent upon each other. With zone-by-zone information, the analysis can much better identify which parts of the study area are most prone to conflagration.

- Adjust the model for urban intermix fuels, if these conditions are applicable to the study area. Fire spreads are much higher in these areas than in urban areas. The analysis will have to digitize in the fuel mix for each cell of the model, and adjust the fire spread model accordingly.

- Add high flow water system boundaries to the model. In some areas of the city, the water system may be designed to provide very high flows: 24" diameter (or larger) transmission pipes (with hydrants) which carry flows on the order of 20,000 gpm or higher. If there are adequate fire department resources available, then almost any fire can be stopped at these locations, even under relatively high winds. Of course, the Water System Lifeline module will have to also be analyzed to determine if these pipes break under the earthquake.

10.4 References

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Chapter 11
Induced Damage Models - Hazardous Materials Release

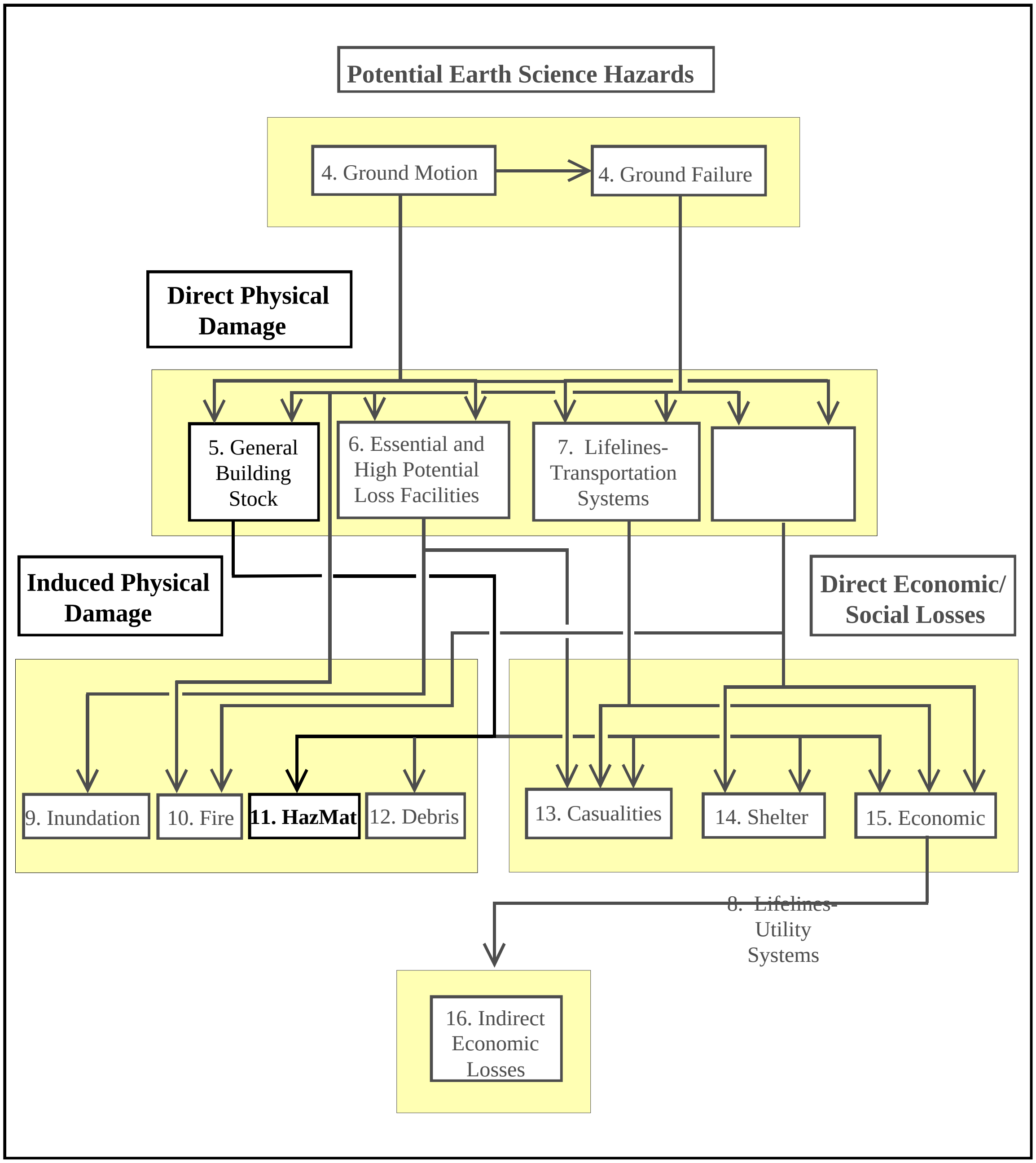
11.1 Introduction

Hazardous materials are those chemicals, reagents or substances that exhibit physical or health hazards, whether the materials are in a usable or waste state. The scale, and hence the consequences, of hazardous materials releases can vary from very small, such as a gallon of paint falling off of shelves, to regional, such as release of toxic chemicals from a processing plant. Most hazardous materials incidents have immediately led to human casualties only in cases where explosions have occurred. Non-explosive hazardous materials incidents, which comprise the vast majority, typically have led to contamination of the environment and temporary health consequences to human beings. Hazardous materials releases can also lead to fires. With specific reference to earthquake caused hazardous materials incidents, the data thus far indicate that there have been no human casualties. The consequences of these incidents have been fires and contamination of the environment, and have led to economic impacts because of the response and clean-up requirements. The methodology highlighting the Hazardous Materials Release component is shown in Flowchart 11.1.

11.1.1 Scope

This loss estimation methodology has been restricted to identifying the location of facilities that contain hazardous material which could lead to a significant immediate demand on health care and emergency response facilities. These types of incidents would include large toxic releases, fires or explosions. Thus, the default database of hazardous material facilites is limited to facilities where large quantities of chemicals that are considered highly toxic, flammable or highly explosive are stored. Estimates of releases that could cause pollution of the environment and the need for long-term clean-up effects are beyond the scope of this methodology.

An exhaustive search of the existing literature for models that can be utilized to predict the likelihood of occurrence of hazardous materials releases during earthquakes was conducted at the beginning of this study. Unfortunately, no directly usable models were found. There were three attempts at modeling that had been made previously (Tierney, et al., 1990, Ravindra, 1992, Los Angeles County Fire Department, 1992). The model developed by Tierney et al. focused on the likelihood of gaseous releases, and its potential effect on surrounding populations. However, it was not found to be suitable for risk assessment efforts by local jurisdiction personnel due to the level of detailed analysis required. The study conducted by Ravindra is in essence identical to the effort by the Los Angeles County Fire Department. This effort is really intended for seismic vulnerability analysis of individual facilities, and requires significant expert input,



Flowchart 11.1: Hazardous Materials Release Relationship to other Modules in the Earthquake Loss Estimation Methodology

including a walk-through inspection. Furthermore, this effort is aimed at large complexes similar to petrochemical facilities, and is not suitable for a more general application. There is, therefore, the need for a more general model that can be used by emergency preparedness officials at the local jurisdiction level so that they can determine the potential for hazardous materials incidents occurring during earthquakes.

Due to the limitations of state-of-the-art hazardous materials release models, this module is restricted to establishing a standardized approach for classifying materials and developing a good database that can be used by local planners to identify those facilities that may be most likely to have significant releases in future earthquakes. A default database of potential sites is provided from an EPA database of hazardous materials sites. This database can be supplemented by the user with local information. A more detailed vulnerability assessment would involve going to individual facilities to determine how chemicals are stored, the vulnerability of buildings and storage tanks and other relevant information.

11.1.2 Classification of Hazardous Materials

The most widely used detailed classification scheme is the one that has been developed by the National Fire Protection Association, and is presented in the 1991 Uniform Fire Code, among other documents. This classification scheme is shown in Table 11.1. The hazards posed by the various materials are divided into two major categories: Physical Hazards and Health Hazards. Depending upon the exact nature of the hazard, these two major categories are divided into subcategories. These subcategories of hazards, with their definitions, and examples of materials that fall within each category, are contained in Appendix 11A and 11B. A more detailed description of these categories, with more extensive examples can be found in Appendix VI-A of the 1991 Uniform Fire Code. Table 11.1 also contains minimum quantities of the materials that must be on site to require permitting according to the Uniform Fire Code. It should be noted that the minimum permit quantities might vary depending upon whether the chemical is stored inside or outside of a building.

11.1.3 Input Requirements and Output Information

The input to this module is essentially a listing of the locations of facilities storing hazardous materials and the types/amounts of the materials stored at the facility. Facilities need only be identified if they use, store or handle quantities of hazardous materials in excess of the quantities listed in Table 11.1. Other facilities that may have hazardous materials, but in quantities less than those listed in Table 11.1 should not be included in the database because it is anticipated that releases of these small quantities will not put significant immediate demands on health and emergency services. However, the user may choose to modify threshold amounts in building the database.

Table 11.1: Classification of Hazardous Materials and Permit Amounts

Label	Material Type	Permit Amount		Hazard Type & Remarks
		Inside Building	Outside Building	
HM01	Carcinogens	10 lbs	10 lbs	Health
HM02	Cellulose nitrate	25 lbs	25 lbs	Physical
HM03	Combustible fibers	100 cubic ft	100 cubic ft	Physical
	Combustible liquids			Physical
HM04	Class I	5 gallons	10 gallons	
HM05	Class II	25 gallons	60 gallons	
HM06	Class III-A	25 gallons	60 gallons	
HM07	Corrosive gases	Any amount	Any amount	Health [1]
HM08	Corrosive liquids	55 gallons	55 gallons	Physical; Health
	Cryogens			
HM09	Corrosive	1 gallon	1 gallon	Health
HM10	Flammable	1 gallon	60 gallons	Physical
HM11	Highly toxic	1 gallon	1 gallon	Health
HM12	Nonflammable	60 gallons	500 gallons	Physical
HM13	Oxidizer (including oxygen)	50 gallons	50 gallons	Physical
HM14	Highly toxic gases	Any amount	Any amount	Health; [1]
HM15	Highly toxic liquids & solids	Any amount	Any amount	Health
HM16	Inert	6,000 cubic ft	6,000 cubic ft	Physical; [1]
HM17	Irritant liquids	55 gallons	55 gallons	Health
HM18	Irritant solids	500 lbs	500 lbs	Health
HM19	Liquefied petroleum gases	> 125 gallons	> 125 gallons	Physical
HM20	Magnesium	10 lbs	10 lbs	Physical
HM21	Nitrate film	(Unclear)	(Unclear)	Health
HM22	Oxidizing gases (including oxygen)	500 cubic feet	500 cubic feet	Physical [1]
	Oxidizing liquids			Physical
HM23	Class 4	Any amount	Any amount	
HM24	Class 3	1 gallon	1 gallon	
HM25	Class 2	10 gallons	10 gallons	
HM26	Class 1	55 gallons	55 gallons	
	Oxidizing solids			Physical
HM27	Class 4	Any amount	Any amount	
HM28	Class 3	10 lbs	10 lbs	
HM29	Class 2	100 lbs	100 lbs	
HM30	Class 1	500 lbs	500 lbs	
	Organic peroxide liquids and solids			Physical
HM31	Class I	Any amount	Any amount	
HM32	Class II	Any amount	Any amount	
HM33	Class III	10 lbs	10 lbs	
HM34	Class IV	20 lbs	20 lbs	
	Other health hazards			Health
HM35	Liquids	55 gallons	55 gallons	
HM36	Solids	500 lbs	500 lbs	

Table 11.1: Classification of Hazardous Materials and Permit Amounts (cont.)

Label	Material Type	Permit Amount		Hazard Type & Remarks
		Inside Building	Outside Building	
HM37	Pyrophoric gases	Any amount	Any amount	Physical [1]
HM38	Pyrophoric liquids	Any amount	Any amount	Physical
HM39	Pyrophoric solids	Any amount	Any amount	Physical
HM40	Radioactive materials	1 m Curie in unsealed source	1 m Curie in sealed source	Health [1]
HM41	Sensitizer, liquids	55 gallons	55 gallons	Health
HM42	Sensitizer, solids	500 lbs	500 lbs	Health
HM43	Toxic gases	Any amount	Any amount	Health [1]
HM44	Toxic liquids	50 gallons	50 gallons	Health
HM45	Toxic solids	500 lbs	500 lbs	Health
HM46	Unstable gases (reactive)	Any amount	Any amount	Physical [1]
	Unstable liquids (reactive)			Physical
HM47	Class 4	Any amount	Any amount	
HM48	Class 3	Any amount	Any amount	
HM49	Class 2	5 gallons	5 gallons	
HM50	Class 1	10 gallons	10 gallons	
	Unstable solids (reactive)			Physical
HM51	Class 4	Any amount	Any amount	
HM52	Class 3	Any amount	Any amount	
HM53	Class 2	50 lbs	50 lbs	
HM54	Class 1	100 lbs	100 lbs	
	Water-reactive liquids			Physical
HM55	Class 3	Any amount	Any amount	
HM56	Class 2	5 gallons	5 gallons	
HM57	Class 1	10 gallons	10 gallons	
	Water-reactive solids			Physical
HM58	Class 3	Any amount	Any amount	
HM59	Class 2	50 pounds	50 pounds	
HM60	Class 1	100 pounds	100 pounds	

[1] Includes compressed gases

To build the hazardous materials database for a selected region, the user should attempt to gather the following information:

- Name of Facility or Name of Company
- Street Address
- City
- County
- State
- Zip Code
- Name of Contact in Company
- Phone Number of Contact in Company
- Standard Industrial Classification (SIC) Code
- Chemical Abstracts Service (CAS) Registry Number
- Chemical Name
- Chemical Quantity

- Hazardous Material Class (From Table 11.1)
- Latitude and Longitude of Facility

The Chemical Abstracts Service (CAS) registry number is a numeric designation assigned by the American Chemical Society's Chemical Abstracts Service and uniquely identifies a specific chemical compound. This entry allows one to conclusively identify a material regardless of the name or naming system used. To obtain this data the user must identify the local agency with which users of hazardous materials must file for permits. Based upon current understanding of the process, this local agency would be the Fire Department for incorporated areas, and the County Health Department for unincorporated areas. The user may opt to use only the information contained in a modified version of the EPA-TRI Database that is provided in the methodology. This database, however, is limited and the user is urged to collect additional inventory.

The output of this module is essentially a database that can be sorted according to any of the fields listed above. It can be displayed on a map and overlaid with other maps.

11.2 Description of Methodology

The analysis here is divided into three levels, as described below:

- Default Analysis: Listing of all facilities housing hazardous materials that are contained in the default hazardous materials database.
- User-Supplied Data Analysis: Listing of all facilities housing hazardous materials that are contained in the default hazardous materials database and refined by the user with locally available information.
- Advanced Data and Models Analysis: Detailed risk assessment for individual facilities, including expert-generated estimates.

11.3 Guidance for Expert-Generated Estimates

A detailed analysis is quite involved and is intended to provide the user with a relatively good estimate of the likelihood of a hazardous materials incident occurring at individual facilities during an earthquake. The detailed analysis therefore provides vulnerabilities of individual facilities. While the model were based primarily on location of facilities and type(s) and quantities of hazardous materials on site, a more detailed analysis is intended to take into account a number of other factors including the level of preparedness of individual facilities and the type of structure within which the hazardous materials are located. To do this detailed analysis, it is necessary to have an expert conduct a detailed analysis of individual facilities.

The level of sophistication to be attained in an analysis can vary significantly, depending upon how the analysis is defined. It is recommended very strongly that the user clearly identify the purpose and scope of the analysis first before engaging an expert to conduct the analysis. Based on the level of analysis expected, the user then has to identify and select an expert, or several experts, to conduct the analysis. In any case, it will be necessary for the expert(s) to conduct a thorough survey and inspection of the facilities. The areas that need to be covered include the following: structures, building contents including equipment, storage areas, tanks, and emergency preparedness. Depending upon the level of the analysis, the experts required could cover the following: a hazardous materials expert, a structural engineer, an emergency planner, and a mechanical engineer. The role(s) each of these experts would play is explained below.

Input Requirements

The most elementary form of detailed analysis would consist of a hazardous materials expert doing a walk through to identify target hazard areas. In most jurisdictions, the fire department personnel are the best trained in issues pertaining to hazardous materials. Many fire departments are also willing to meet with major users of hazardous materials to do what is termed “pre-planning”. In this effort, fire departments visit the facilities of users, identify areas that they think are particularly vulnerable, and suggest improvements. If there were code violations, the fire department personnel would point this out. In highly industrialized areas, there are consulting firms that are capable of conducting this assessment. The smaller consulting firms tend to be comprised only of individuals with expertise in hazardous materials issues.

It must be borne in mind that when assessing the potential for hazardous materials releases during earthquakes, the performance of the structure and the performance of nonstructural items are both important. Another very important factor is the level of preparedness, especially where it pertains to the ability to contain an incident and prevent it from spreading or enlarging.

The structural and nonstructural vulnerability of a hazardous materials facility are assessed by a qualified structural engineer. For example, the integrity of an above ground storage tank, containing 100,000 gallons of petroleum, should be evaluated by a structural engineer.

A large number of hazardous materials incidents during earthquakes have occurred at locations where the structure itself suffered no damage. This has been due to the manner in which the hazardous materials are stored and used within the buildings or structures. Generally, it is the extent to which nonstructural hazard mitigation measures have been implemented that determines the vulnerability of the contents. At the present time there is no profession that specializes in “nonstructural engineering”. A reference on nonstructural hazard mitigation measures has been written by Reitherman (1983). A more specific paper discussing hazard prevention techniques in the laboratory has been written by Selvaduray (1989). Though not directly pertaining to industrial facilities, FEMA has developed a guide for nonstructural hazard mitigation in hospitals (FEMA, 1989). Hazard mitigation strategies, particularly where they pertain to preventing toxic gas releases during earthquakes, have been studied by ABAG, and are contained in a special report prepared by ABAG (1991).

In conducting a detailed analysis, it is important not only to assess the potential for occurrence of incidents, but it is also important to assess the capability of containing incidents and preventing them from spreading or becoming enlarged. The level of preparedness of the individual facilities generally determines this. There have been a number of cases where the incidents would have been smaller than they actually were, had the organization/facility had the capability to respond in a timely manner. The type of expert needed here is an "Emergency Planner". Unfortunately, it is not easy to find an emergency planner who specializes in assessing individual facilities. Here again, perhaps the most qualified and educated personnel are fire department personnel. In most cases, hazardous materials consultants also address issues pertaining to response. In the case when an expert is not available, the document by the U.S. Environmental Protection Agency (EPA, 1987), which provides technical guidance for hazards analysis and emergency planning for extremely hazardous substances is an excellent guide. Another useful guide is the "Hazardous Materials Emergency Response Guide" published by the National Response Team (1987). The user should keep in mind that both of these documents are quite general in nature, and do not address earthquake concerns specifically. Nevertheless, in the absence of more specific information, these guides are definitely useful in getting the user started towards assessing the risks.

Depending upon the type of facility, there could also be a large number of mechanical systems, including piping that either utilize or carry hazardous materials. Examples of such facilities include petroleum refineries, semiconductor processing facilities, and polymer resin synthesis facilities. In such cases, the type of expert capable of conducting an adequate vulnerability analysis of the mechanical and piping systems would be a mechanical engineer. It should be pointed out that mechanical engineering is a very broad field, and the particular type of mechanical engineer who would be suitable for a task such as the one posed here would be one with a very strong background in plant safety, and preferably also in structural analysis. A number of hazardous materials releases during past earthquakes have occurred in mechanical and piping systems. This component should therefore not be ignored. A book on assessing the earthquake vulnerability of building equipment has been written by McGavin (1983). This book provides particularly valuable information on anchoring of equipment. One approach to assessing the vulnerability of hazardous materials piping systems has been developed and presented by Kircher (1990), and can potentially be utilized by mechanical engineers having the capability to conduct particularly sophisticated analysis.

There are two documents that provide a general methodology for assessing the earthquake vulnerability of entire facilities, particularly those that contain hazardous materials. One such document is the "Proposed Guidance for RMPP Seismic Assessments" contained within the Los Angeles County Fire Department's Risk Management and Prevention Program Guidelines. This document provides guidelines for assessing the earthquake vulnerability of facilities that use hazardous materials, especially Acutely Hazardous Materials (AHM). However, the methodology provided does require a structural engineer. On the positive side, there are relatively detailed guidelines for assessing the vulnerability of piping systems. Ravindra (1992) has presented an approach, that is very similar to the one developed by the Los Angeles County Fire Department, for seismic evaluation of hazardous materials facilities.

Output Information

Ideally, upon completion of a detailed analysis, the user will have a very good idea of the vulnerability (ies) contained within each facility. The user will have a relatively good grasp of the potential for occurrence of hazardous materials releases, during earthquakes, at each of the facilities analyzed. While this might not be a quantified probability number, the results of the analysis should provide sufficient information to categorize the likelihood in terms of “high, medium, or low”. In addition to the overall likelihood, the user should also be able to identify the locations within each facility where hazardous materials releases might occur. This can be particularly important for larger facilities that cover several acres. It is only by identifying specific locations within the larger facilities that adequate response can be planned for. Another piece of information that the user should obtain from an expert-assisted analysis is the likely consequence of a hazardous materials release. Particularly important here is the scope of the release, and the manner in which it would affect the surrounding area. It is expected that this can be determined by combining the analysis data with other data such as hazard, type of the material, phase of the material (solid, liquid or gas), prevailing weather conditions, and demographics of the surrounding region.

The analysis should also provide the user with the ability to assess the response capability of each facility inspected. Depending upon the response capability that each facility has, the user would need to adjust his/her response capability to account for this. In general, the larger industrial facilities, such as petroleum refineries, tend to have relatively extensive response capability in-house. As such, they would be able to be the “first responders”, with the local jurisdictions providing the necessary backup capabilities. On the other hand, if the larger industrial facilities do not have sufficient capabilities to respond to hazardous materials releases, the analysis would provide the local emergency preparedness officials with the opportunity to require such facilities to increase their response capability.

11.4 References

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Appendix 11A
Listing of Chemicals contained in SARA Title III, including their CAS Numbers, Hazards and Treshold Planning Quantities

CAS Number	Chemical Name	Hazard	Treshold Planning Quantity (pounds)
00075-86-5	Acetone cyanohydrin	Poison	1,000
01752-30-3	Acetone thiosemicarbazide	Poison	1,000 +
00107-02-8	Acrolein	Flammable liquid & poison	500
00079-06-1	Acrylamide	Poison	1,000 +
00107-13-1	Acrylonitrile	Flammable liquid & poison	10,000
00814-68-6	Acrylyl chloride	Poison	100
00111-69-3	Adiponitrile	Poison	1,000
00116-06-3	Aldicarb	Deadly poison	100 +
00309-00-2	Aldrin	Poison	500 +
00107-18-6	Allyl alcohol1	Flammable liquid & poison	1,000
00107-11-9	Allylamine	Flammable liquid & poison	500
20859-73-8	Aluminum phosphide	Flammable solid & poison	500
00054-62-6	Aminopterin	Poison	500 +
00078-53-5	Amiton	Deadly poison	500
03734-97-2	Amiton oxalate	Deadly poison	100 +
07664-41-7	Ammonia, anhydrous	Poison	500
00300-62-9	Amphetamine	Deadly poison	1,000
00062-53-3	Aniline	Poison	1,000
00088-05-1	Aniline, 2,4,6-trimethyl	Poison	500
07783-70-2	Antimony pentafluoride	Corrosive to skin, eyes, mucuous membranes	500
01397-94-0	Antimycin A	Poison	1,000 +
00086-88-4	Antu	Poison	500 +
01303-28-2	Arsenic pentoxide	Poison	100 +
01327-53-3	Arsenous oxide	Poison	100
07784-34-1	Arsenous trichloride	Poison	500
07784-42-1	Arsine	Poison gas & flammable gas	100
02642-71-9	Azinphos-ethyl	Poison	100 +
00086-50-0	Azinphos-methyl	Poison	10 +
00098-87-3	Benzal chloride	Moderately toxic	500
00098-16-8	Benzehamine,3-(trifluoromethyl)-	Poison	500
00100-14-1	Benzene, 1-(chloromethyl)-4-nitro-	Poison	500 +
00098-05-5	Benzenearsonic acid	Deadly poison	10 +
03615-21-2	Benzimidazole, 4,5-dichloro-2-(trifluoromethyl)	Poison	500 +
00098-07-7	Benzotrichloride (benzoic trichloride)	Corrosive & poison	100
00100-44-7	Benzyl chloride	Corrosive & poison	500
00140-29-4	Benzyl cynaide	Poison	500
15271-41-7	Bicyclo [2,2,1]heptane-2-carbonitrile,5-chloro-6((((methylamino)carbonyl)oxy)imino)-(1S-(1-alpha,2-beta,4-alpha,5-alpha,6E))-	Poison	500 +
00111-44-4	Bis(2chloroethyl)ether	Poison	10,000
00542-88-1	Bis(chloromethyl)ether	Poison & carcinogen	100
00534-07-6	Bis(chloromethyl)ketone	Poison	10 +
04044-65-9	Bitoscanate	Poison	500 +
10294-34-5	Boron trichloride	Corrosive, poison, irritant & reactive with water	500
07637-07-2	Boron trifluoride	Poison & strong irritant	500
00353-42-4	Borontrifluoride compound with methyl ether (1:1)	Flammable, corrosive & poison	1,000
28772-56-7	Bromadiolone	Deadly poison	100 +
07726-95-6	Bromine	Corrosive & poison	500
01306-19-0	Cadmium oxide	Poison	100 +
02223-93-0	Cadmium stearate	Poison	1,000 +
07778-44-1	Calcium arsenate	Poison & carcinogen	500 +
00056-25-7	Cantharidin	Deadly poison	100 +
00051-83-2	Carbachol chloride	Deadly poison	500 +

CAS Number	Chemical Name	Hazard	Treshold Planning Quantity (pounds)

26419-73-8	Carbamic acid, methyl-O-(((2,4-dimethyl-1,3-dithiolan-2-yl)methylene)amino)-	Poison	100 +
01563-66-2	Carbofuran	Poison	10 +
00075-15-0	Carbon disulfide	Flammable liquid & poison	10,000
000786-19-6	Carbophenothion	Poison	500
00057-74-9	Chlordane	Flammable liquid & poison	1,000
00470-90-6	Chlorfenvinfos	Poison	500
07782-50-5	Chlorine (not muratic acid or bleach)	Poison gas	100
24934-91-6	Chlormephos	Poison	500
00999-81-5	Chlormequat chloride		100 +
00079-11-8	Chloroacetic acid	Corrosive & poison	100 +
00107-07-3	Chloroethanol	Flammable liquid & poison	500
00627-11-2	Chloroethyl chloroformate	Poison	1,000
00555-77-1	Tris(2-chloroethyl)amine	Moderately toxic	100
00067-66-3	Chloroform	Poison	10,000
00107-30-2	Chloromethyl methyl ether	Flammable liquid & poison	100
03691-35-8	Chlorophacinone	Poison	100 +
01982-47-4	Chloroxuron	Poison	500 +
21923-23-9	Chlorthiophos	Poison	500
10025-73-7	Chromic chloride	Poison	1 +
10210-68-1	Cobalt carbonyl	Poison	10 +
62207-76-5	Cobalt,((2,2'-(1,2-ethanediylbis(nitrilomethylidyne))bis(6-fluorophenolato))(2-)-N,N',O,O')-	Poison	100+
00064-86-6	Colchicine	Poison	10 +
00056-72-4	Coumaphos	Poison	100 +
05836-29-3	Coumatetralyl	Poison	500 +
00095-48-7	Othro-cresol	Poison	1,000 +
00535-89-7	Crimidine	Deadly poison	100 +
00123-73-9	Crotonaldehyde	Poison	1,000
04170-30-3	E-crotonaldehyde	Flammable liquid & poison	1,000
00506-68-3	Cyanogen bromide	Poison	500 +
00506-78-5	Cyanogen iodide	Poison	1,000 +
02636-26-2	Cyanophos	Poison	1,000
00675-14-9	Cyanuric fluoride	Poison	1000
00066-81-9	Cycloheximide	Poison	100 +
000108-91-8	Cyclohexylamine	Flammable liquid & poison	10,000
17702-41-9	Decaborane (14)		500 +
08065-48-3	Demeton	Deadly poison	500
00919-86-8	Demeton-s-methyl	Poison	500
10311-84-9	Dialifor	Poison	100 +
19287-45-7	Diborane	Flammable gas & poison	100
00110-57-6	Trans-1,4-dichlorobutene	Poison	500
00149-74-6	Dichloromethylphenylsilane	Flammable liquid & poison	1,000
00062-73-7	Dichlorvos	Poison	1,000
00141-66-2	Dicrotophos	Poison	100
01464-53-5	Diepoxybutane	Poison	500
00814-49-3	Diethyl chlorophosphate	Deadly poison	500
01642-54-2	Diethylcarbamazine citrate	Poison	100+
00071-63-6	Digitoxin	Deadly poison	100+
02238-07-5	Diglycidyl ether	Poison	1,000
20830-75-5	Digoxin	Deadly poison	10+
00115-26-4	Dimefox	Poison	500
00060-51-5	Dimethiate	Poison	500+
06923-22-4	3-(Dimethoxy phosphinyloxy)-N-methyl-cis croton-amide(monocrotophos)	Poison	10
00075-78-5	Dimethyldichlorosilane	Poison & irritant	500
00057-14-7	Dimethylhydrazine	Flammable liquid & poison	1,000
00099-98-9	Dimethyl-p-phenylenediamine	Poison	10+
02524-03-0	Dimethyl phosphochloridothioate	Corrosive & poison	500
00077-78-1	Dimethyl sulfate	Corrosive & poison	500
00644-64-4	Dimetilan	Poison	500+
00534-52-1	4,6-Dinitro-o-cresol	Poison	10+

CAS Number	Chemical Name	Hazard	Treshold Planning Quantity (pounds)
00088-85-7	Dinoseb	Poison	100+
01420-07-1	Dinoterb	Poison	500+
00078-34-2	Dioxathion	Poison	500

00082-66-6	Diphacinone	Poison	10+
00152-16-9	Diphosphoramide, octamethyl	Poison	100
00298-04-4	Disulfoton	Poison	500
00514-73-8	Dithiazamine iodide	Poison	500+
00541-53-7	Dithiobiuret	Poison	100+
00316-42-7	Emetine, dihydrochloride	Poison	1+
00115-29-7	Endosulfan	Poison	10+
02778-04-3	Endothion	Poison	500+
00072-20-8	Endrin	Poison	500+
00106-89-8	Epichlorohydrin	Flammable liquid & poison	1,000
02104-64-5	EPN	Poison	100+
00050-14-6	Ergocalciferol	Poison	1,000+
00379-79-3	Ergotamine tartate	Poison	500+
01622-32-8	Ethanesulfonyl chloride,2-chloro	Poison	500
10140-87-1	Ethanol,1,2-dichloroacetate	Combustible & poison	1,000
00563-12-2	Ethion	Poison	1,000
13194-48-4	Ethoprophos	Poison	1,000
00538-07-8	Ethylbis(2-chloroethyl)amine	Deadly poison	500
00107-15-3	Ethylenediamine	Corrosive, flammable liquid, irritant	10,000
00371-62-0	Ethylene fluorohydrin	Poison	10
00151-56-4	Ethyleneimine	Flammable liquid & poison	500
00075-21-8	Ethylene oxide	Flammable gas & poison	1,000
00542-90-5	Ethylthiocyanate	Poison	10,000
22224-92-6	Fenamiphos	Poison	10+
00122-14-5	Fenitrothion	Poison	500
00115-90-2	Fensulfothion	Poison	500
04301-50-2	Fluenetil	Poison	100+
07782-41-4	Fluorine	Oxidizer & poison	500
00640-19-7	Fluoroacetamide (1061)	Poison	100+
00144-49-0	Fluoroacetic acid	Poison	10+
00359-06-8	Fluoroacetyl chloride	Poison	10
00051-21-8	Fluorouracil	Poison	500+
00944-22-9	Fonofos	Poison	500
00050-00-0	Formaldehyde	Combustible liquid & poison	500
00107-16-4	Formaldehyde cyanohydrin	Poison	1,000
23422-53-9	Formetanate hydrochloride	Poison	500+
02540-82-1	Formothion	Poison	100
17702-57-7	Formparanate	Poison	100+
21548-32-3	Fosthientan	Poison	500
03878-19-1	Fuberidazole	Poison	100+
00110-00-9	Furan	Flammable liquid & poison	500
13450-90-3	Gallium trichloride	Poison	500+
00077-47-4	Hexachlorocyclopentadiene	Corrosive & deadly poison	100
04835-11-4	Hexamethylenediamine,N,N-dibutyl	Poison	500
00302-01-2	Hydrazine	Flammable liquid, corrosive & poison	1,000
00074-90-8	Hydrocyanic acid	Deadly poison	100
07647-01-0	Hydrogen chloride (gas only)	Highly corrosive irritant	500
07664-39-3	Hydrogen fluoride	Corrosive & poison	100
07722-84-1	Hydrogen peroxide (conc. >52%)	Oxidizer, moderately toxic	1,000
07783-07-5	Hydrogen selenide	Flammable gas & deadly poison	10
07783-06-4	Hydrogen sulfide	Flammable gas & poison	500
00123-31-9	Hydroquinone	Poison	500+
13463-40-6	Iron pentacarbonyl	Poison	100
00297-78-9	Isobenzan	Poison	100+
00078-82-0	Isobutyronitrile	Flammable liquid & poison	1,000
00102-36-3	Isocyanic aicd,3,4-dichlorophenyl ester	Poison	500+
00465-73-6	Isodrin	Poison	100+
CAS Number	**Chemical Name**	**Hazard**	**Treshold Planning Quantity (pounds)**
00055-91-4	Isofluorphate	Poison	100
04098-71-9	Isophorone diisocyanate	Poison	100
00108-23-6	Isopropyl chloroformate	Flammable liquid & poison	1,000
00119-38-0	Isopropylmethylpyrazolyl dimethylcarbamate	Poison	500
00078-97-7	Lactonitrile	Poison	1,000
21609-90-5	Leptophos	Poison	500+
00541-25-3	Lewisite	Poison	10

00058-89-9	Lindane	Poison	1,000+
07580-67-8	Lithium hydride	Flammable solid & poison	100
00109-77-3	Malononitrile	Poison	500+
12108-13-3	Mangenese tricarbonyl methylcyclopentadienyl	Poison	100
00950-10-7	Mephosfolan	Poison	500
01600-27-7	Mercuric acetate	Poison	500+
07487-94-7	Mercuric chloride	Poison	500+
21908-53-2	Mercuric oxide	Powerful oxidant	500+
10476-95-6	Methacrolein diacetate	Poison	1,000
00760-93-0	Methacrylic anhydride	Poison	500
00126-98-7	Methylacrylonitrile	Poison	500
00920-46-7	Methacryloyl chloride	Poison	100
30674-80-7	Methacryloyloxyethylisocyanate	Poison	100
10265-92-6	Methamidophos	Poison	100+
00558-25-8	Methanesulfonyl fluoride	Poison	1,000
00950-37-8	Methidathion	Poison	500+
02032-65-7	Methiocarb	Poison	500+
16752-77-5	Methomyl	Poison	500+
00151-38-2	Methoxyethylmercuric acetate	Poison	500+
00074-83-9	Methyl bromide	Poison gas	1,000
00080-63-7	Methyl 2-chloroacrylate	Moderately toxic	500
00079-22-1	Methyl chloroformate	Flammable liquid, corrosive & poison	500
00060-34-4	Methyl hydrazine	Flammable liquid, corrosive, poison	500
00624-83-9	Methyl isocyanate	Flammable liquid & poison	500
00556-61-6	Methyl isothiocyanate	Flammable liquid & poison	500
00074-93-1	Methyl mercaptan	Flammable gas & poison	500
00502-39-6	Methylmercuric dicyanamide	Poison	500+
03735-23-7	Methyl phenkapton	Poison	500
00676-97-1	Methyl phosphonic dichloride	Corrosive & poison	100
00556-64-9	Methyl thiocyanate	Poison	10,000
00075-79-6	Methyl trichlorosilane	Flammable liquid, corrosive & poison	500
00079-84-4	Methyl vinyl ketone		10
01129-41-5	Metolcarb	Poison	100+
07786-34-7	Mevinphos	Poison	500
00315-18-4	Mexacarbate	Poison	500+
00050-07-7	Mitomycin C	Poison	500+
06923-22-4	Monocrotophos	Poison	10+
02763-96-4	Muscinol	Poison	10,000
00505-60-2	Mustard gas	Poison	500
13463-39-3	Nickel carbonyl	Flammable liquid & poison	1
00054-11-5	Nicotine	Poison	100
00065-30-5	Nicotine sulfate	Poison	100+
07697-37-2	Nitric acid (.40% pure)	Corrosive, oxidizer & poison	1,000
10102-43-9	Nitric oxide	Poison gas	100
00098-95-3	Nitrobenzene	Poison	10,000
01122-60-7	Nitrocyclohexane	Poison	500
10102-44-0	Nitrogen dioxide	Oxidizer & moderately toxic	100
00051-75-2	Nitrogen mustard	Deadly poison	10
00062-75-9	N-Nitrosodimethylamine	Poison	1,000
00991-42-4	Norbormide	Poison	100+
PMN-82-147	Organorhodium complex	Flammable & toxic	10+
00630-60-4	Ouabain	Poison	100+
23135-22-0	Oxamyl	Poison	100+
CAS Number	**Chemical Name**	**Hazard**	**Treshold Planning Quantity (pounds)**
00078-71-7	Oxetane,3,3,-bis(chloromethyl)-	Poison	500
02497-07-6	Oxydisulfoton	Poison	500
10028-15-6	Ozone	Poison	100
01910-42-5	Paraquat	Poison	10+
02074-50-2	Paraquat methosulfate	Poison	10+
00056-38-2	Parathion	Poison	100
00298-00-0	Parathion-methyl	Poison	100+
13002-03-8	Paris green	Poison	500+
19624-22-7	Pentaborane	Flammable liquid & poison	500
02570-26-5	Pentadecylamine	Poison	100+
00079-21-0	Peracetic acid	Corrosive & poison	500

00594-42-3	Perchloromethylmercaptan	Poison	500
00108-95-2	Phenol	Poison	500+
04418-66-0	Phenol,2,2-thiobis(4-chloro-6-methyl)	Poison	100+
00064-00-6	Phenol,3-(1-methylethyl)-methylcarbamate	Poison	500+
00058-36-6	Phenoarsazine 10,10-oxydi-	Poison	500+
00696-28-6	Phenyl dichloroarsine	Poison	500
00059-88-1	Phenylhydrazine hydrochloride	Poison	1,000+
00062-38-4	Phenylmercury acetate	Poison	500+
02097-19-0	Phenylsilatrane	Poison	100+
00103-85-5	Phenylthiourea	Poison	100+
00298-02-2	Phorate	Poison	10
04104-14-7	Phosacetim	Poison	100+
00947-02-4	Phosfolan	Poison	100+
00075-44-5	Phosgene	Poison gas	10
00732-11-6	Phosmet	Poison	10+
13171-21-6	Phosphamidon	Poison	100
07803-51-2	Phosphine	Flammable & poison gas	500
02665-30-7	Phosphonothioic acid, methyl-o-(4-nitrophenol)o-phenyl ester	Poison	500
50782-69-9	Phosphonothioic acid, methyl-s-(2-(bis(1-methylethyl)amino)o-ethyl ester`	Poison	100
02703-13-1	Phosphonothioic acid methyl,-o-ethyl-o-4-(methylthio)phenyl ester	Deadly poison	500
03254-63-5	Phosphoric acid, dimethyl,4-(mehtylthio)phenyl ester	Poison	500
02587-90-8	Phosphorothioic aicd,o,o-dimethyl-s-(2-methyl-thio-ethyl ester	Poison	500
07723-14-0	Phosphorus	Flammable solid & poison	100
10025-87-3	Phosphorus oxychloride	Corrosive, irritant & poison	500
10026-13-8	Phosphorus pentachloride	Corrosive & poison	500
01314-56-3	Phosphorus pentoxide	Corrosive & poison	10
07719-12-2	Phosphorus trichloride	Corrosive & poison	1,000
00057-47-6	Physostigmine	Poison	100+
00057-64-7	Physostigmine, salicylate (1:1)	Poison	100+
00124-87-8	Picrotoxin	Poison	500+
00110-89-4	Piperidine	Poison	1,000
23505-41-1	Pirimifos-ethyl	Poison	1,000
10124-50-2	Potassium arsenite	Poison	500+
00151-50-8	Potassium cyanide	Deadly poison	100
00506-61-6	Potassium silver cyanide	Poison & irritant	500
02631-37-0	Promecarb	Poison	500+
00106-96-7	Propagyl bromide	Flammable liquid & deadly poison	10
00057-57-8	beta-Propiolactone	Poison	500
00107-12-0	Propionitrile	Flammable liquid & poison	500
00542-76-7	Propionitrile, 3-chloro	Poison	1,000
00070-69-9	Propiophenone,4-amino	Poison	100+
00109-61-5	Propyl chloroformate	Flammable liquid, corrosive & poison	500
00075-56-9	Propylene oxide	Flammable liquid & poison	10,000
00075-55-8	Propyleneimene	Flammable liquid & poison	10,000
02275-18-5	Prothoate	Poison	100+
00129-00-0	Pyrene	Poison	1,000+

CAS Number	Chemical Name	Hazard	Treshold Planning Quantity (pounds)
00140-76-1	Pyridine,2-methyl-5-vinyl	Poison	500
00504-24-5	Pyridine,4-amino	Poison	500+
01124-33-0	Pyridine,4-nitro-,1-oxide	Poison	500+
53558-25-1	Pyriminil	Poison	100+
14167-18-1	Salcomine	Poison	500+
00107-44-8	Sarin	Deadly poison	10
07783-00-8	Selenous acid	Poison	1,000+
07791-23-3	Selenium oxychloride	Poison	500
00563-41-7	Semicarbazide hydrochloride	Poison	1,000+
03037-72-7	Silane, (4-aminobutyl)diethoxymethyl	Poison	1,000
07631-89-2	Sodium arsenate	Poison	1,000+
07784-46-5	Sodium arsenite	Deadly poison	500+
26628-22-8	Sodium azide	Poison	500
00124-65-2	Sodium cacodylate	Poison	100+
00143-33-9	Sodium cyanide	Deadly poison	100

00062-74-8	Sodium fluoroacetate	Deadly poison	10+
13410-01-0	Sodium selenate	Poison	100+
10102-18-8	Sodium selenite	Poison	100+
10102-20-2	Sodium tellurite	Poison	500+
00900-95-8	Stannane, acetoxytriphenyl	Poison	500+
00057-24-9	Strychnine	Poison	100+
00060-41-3	Strychnine, sulfate	Poison	100+
03689-24-5	Sulfotep	Poison	500
03569-57-1	Sulfoxide,3-chloropropyloctyl	Poison	500
07446-09-5	Sulfur dioxide	Poison gas	500
07783-60-0	Sulfur tetrafluoride	Poison gas	100
07446-11-9	Sulfur trioxide	Corrosive & poison	100
07664-93-9	Sulfuric acid (>93%)	Corrosive & poison	1,000
00077-81-6	Tabun	Poison	10
13494-80-9	Tellurium	Poison	500+
07783-80-4	Tellarium hexafluoride	Poison gas	100
00107-49-3	TEPP	Poison	100
13071-79-9	Terbufos	Deadly poison	100
00078-00-2	Teraethyllead	Flammable liquid & poison	100
00597-64-8	Tetraethyltin	Poison	100
00075-74-1	Tetramethyllead	Poison	100
00509-14-8	Tetranitromethane	Oxidizer & poison	500
10031-59-1	Thallium sulfate	Poison	100+
06533-73-9	Thallous carbonate	Poison	100+
07791-12-0	Thallous chloride	Poison	100+
02757-18-8	Thallous malonate	Poison	100+
07446-18-6	Thallous sulfate	Poison	100+
02231-57-4	Thiocarbazide	Poison	1,000+
39196-18-4	Thiofanox	Poison	100+
00297-97-2	Thioazin	Poison	500
00108-98-5	Thiophenol	Flammable liquid & poison	500
00079-19-6	Thiosemicarbazide	Poison	100+
05344-82-1	Thiourea, (2-chlorophenyl)	Poison	100+
00614-78-8	Thiourea (2-methylphenyl)	Poison	500+
07550-45-0	Titanium tetrachloride	Corrosive & poison	100
00584-84-9	Toluene 2,4-diisocyanate	Poison	500
00091-08-7	Toluene 2,6-diisocyanate	Poison	100
08001-35-2	Toxaphene	Poison	500+
01031-47-6	Triamiphos	Poison	500+
24017-47-8	Triazofos	Poison	500
00076-02-8	Trichloroacetyl chloride	Corrosive & moderately toxic	500
01558-25-4	Trichloro(chloromethyl)silane	Poison	100
27137-85-5	Trichloro(chlorophenyl)silane	Corrosive & poison	500
00115-21-9	Trichloroethylsilane	Flammable liquid & poison	500
00327-98-0	Trichloronate	Poison	500
00098-13-5	Trichlorophenylsilane	Corrosive & poison	500
00998-30-1	Triethoxysilane	Poison	500

CAS Number	Chemical Name	Hazard	Treshold Planning Quantity (pounds)
00075-77-4	Trimethylchlorosilane	Flammable liquid, corrosive & moderately toxic	1,000
00824-11-3	Trimethylolpropane phosphate	Poison	100+
01066-45-1	Trimethyltin chloride	Deadly poison	500+
00639-58-7	Triphenyltin chloride	Poison	500+
02001-95-8	Valinomycin	Poison	1,000+
01314-62-1	Vanadium pentoxide	Poison	100+
00108-05-4	Vinyl acetate monomer	Flammable liquid & moderately toxic	1,000
00081-81-2	Warfarin	Poison	500+
00129-06-6	Warfarin sodium	Poison	100+
28347-13-9	Xylene dichloride	Poison	100+
58270-08-9	Zinc, dichloro(4,4-dimethyl-5((((methylamino)carbonyl)oxino)pentanenitrile)-,(T-4)	Poison	100+
01314-84-7	Zinc phosphide	Flammable solid & poison	500

Note: For the Treshold Planning Quantities marked with a "+", the quantity listed applies only if in powdered form and with a particle size of less than 100 microns, or is handled in solution or molten form, or has a NFPA rating for reactivity of 2, 3 or 4. Otherwise the Treshold Planning Quantity is 10,000 lbs. The material is still required to be reported on an annual inventory at the Treshold Planning Quantity or 500 lbs, whichever is less.

Source of hazard information: N. Irving San and Richard J. Lews, Sr., Dangerous Properties of Industrial Materials, Seventh Edition, Volumes I - III, Van Nostrand Reinhold, New York, (1989).

Appendix 11B
Listing of Chemicals contained in the TRI Database, including their CAS Numbers and Hazards

CAS NUMBER	CHEMICAL NAME	HAZARDS
75-07-0	Acetaldehyde	Poison
60-35-5	Acetamide	Experimental carcinogen
67-64-1	Acetone	Moderately toxic
75-05-8	Acetonitrile	Poison
53-96-3	2-Acetylaminofluorene	Moderately toxic
107-02-8	Acrolein	Poison
79-06-1	Acrylamide	Poison
79-10-7	Acrylic acid	Poison
107-13-1	Acrylonitrile	Poison
309-00-2	Aldrin	Poison
107-05-1	Allyl chloride	Poison
7429-90-5	Aluminum (fume or dust)	Not considered a industrial poison
1344-28-1	Aluminum oxide	Experimental tumorigen
117-79-3	2-Aminoanthraquinone	Experimental carcinogen
60-09-3	4-Aminoazobenzene	Poison
92-67-1	4-Aminobiphenyl	Poison
82-28-0	1-Amino-2-methylanthraquinone	Experimental neoplastigen
7664-41-7	Ammonia	Poison
6484-52-2	Ammonium nitrate (solution)	Powerful oxidizer & an allergen
7783-20-2	Ammonium sulfate (solution)	Moderately toxic
62-53-3	Aniline	Poison
90-04-0	o-Anisidine	Moderately toxic
109-94-9	p-Anisidine	Moderately toxic
134-29-2	o-Anisidine hydrochloride	Experimental carcinogen
120-12-7	Anthracene	Experimental tumorigen
7440-36-0	Antimony	Poison
7440-38-2	Arsenic	Carcinogen
1332-21-4	Asbestos (friable)	Carcinogen
7440-39-3	Barium	Poison
98-87-3	Benzal chloride	Poison
55-21-0	Benzamide	Moderately toxic
71-43-2	Benzene	Poison
92-87-5	Benzidine	Poison
98-07-7	Benzoic trichloride (Benzotrichloride)	Poison
98-88-4	Benzoyl chloride	Carcinogen
94-36-0	Benzoyl peroxide	Poison
100-44-7	Benzyl chloride	Poison
7440-41-7	Beryllium	Deadly poison
92-52-4	Biphenyl	Poison
111-44-4	Bis(2-chloroethyl) ether	Poison
542-88-1	Bis(chloromethyl) ether	Poison
108-60-1	Bis(2-chloro-1-methyulethyl) ether	Poison
103-23-1	Bis(2-ethylhexyl) adipate	Experimental carcinogen
75-25-2	Bromoform (Tribromomethane)	Poison
74-83-9	Bromomethane (methyl bromide)	Poison
106-99-0	1,3-Butadiene	Experimental carcinogen
141-32-2	Butyl acrylate	Moderately toxic
71-36-3	n-Butyl alcohol	Poison
78-92-2	sec-Butyl alcohol	Poison
75-65-0	tert-Butyl alcohol	Moderately toxic
85-68-7	Butyl benzyl phthalate	Moderately toxic
106-88-7	1,2-Butylene oxide	Moderately toxic
123-72-8	Butyraldehyde	Moderately toxic
2650-18-2	C.I. Acid Blue 9, diammonium salt	Poison
3844-45-9	C.I. Acid Blue, disodium salt	Experimental neoplastigen
4680-78-8	C.I. Acid Green 3	Experimental tumorigen
569-64-2	C.I. Basic Green 4	Poison
989-38-8	C.I. Basic Red 1	Poison
1937-37-7	C.I. Direct black 38	Experimental tumorigen
2602-46-2	C.I. Direct Blue 6	Experimental carcinogen

CAS NUMBER	CHEMICAL NAME	HAZARDS
16071-86-6	C.I. Direct Brown 95	Experimental carcinogen
2832-40-8	C.I. Disperse Yellow 3	Experimental tumorigen
3761-53-3	C.I. Food Red 5	
81-88-9	C.I. Food Red 15	Poison
3118-97-6	C.I. Solvent Orange 7	Experimental carcinogen
97-56-3	C.I. Solvent Yellow 3	Experimental carcinogen
842-07-9	C.I. Solvent Yellow 14	Experimental carcinogen
492-80-8	C.I. Solvent Yellow 34 (Auramine)	Poison
128-66-5	C.I. Vat Yellow 4	Experimental carcinogen
7440-43-9	Cadmiun	Poison
156-62-7	Calcium cyanamide	Poison
133-06-2	Captan	Moderately toxic
63-25-2	Carbaryl	Poison
75-15-0	Carbon disulfide	Poison
56-23-5	Carbon tetrachloride	Poison
463-58-1	Carbonyl sulfide	Poison
120-80-9	Catechol	Moderately toxic
133-90-4	Chloramben	Experimental carcinogen
57-74-9	Chlordane	Poison
7782-50-5	Chlorine	Moderately toxic
10049-04-4	Chlorine dioxide	Moderately toxic
79-11-8	Chloroacetic acid	Poison
532-27-4	2-Chloroacetophenone	Poison
108-90-7	Chlorobenzene	Poison
510-15-6	Chlorobenzilate	Experimental carcinogen
75-00-3	Chloroethane	Mildly toxic
67-66-3	Chloroform	Poison
74-87-3	Chloromethane (Methyl chloride)	Mildly toxic
107-30-2	Chloromethyl methyl ether	Poison
126-99-8	Chloroprene	Poison
1897-45-6	Chlorothalonil	Moderately toxic
7740-47-3	Chromium	Poison
7440-48-4	Cobalt	Poison
7440-50-8	Copper	Experimental tumorigen
120-71-8	p-Cresidine	Moderately toxic
1319-77-3	Cresol (mixed isomers)	Moderately toxic
108-39-4	m-Cresol	Poison
95-48-7	o-Cresol	Poison
106-44-5	p-Cresol	Poison
98-82-8	Cumene	Moderately toxic
80-15-9	Cumene hydroperoxide	Moderately toxic
135-20-6	Cupferron	Poison
110-82-7	Cyclohexane	Poison
94-75-7	2,4-D (Acetic acid,(2,4-dichlore-phenoxy))	Poison
1163-19-5	Decabromodiphenyl oxide	Experimental neoplastigen
2303-16-4	Diallate	Poison
615-05-4	2,4-Diaminoanisole	Poison
39156-41-7	2,4-Diaminoanisole sulfate	Poison
101-80-4	4,4-Diaminophenyl ether	Poison
25376-45-8	Diaminotoluane (mixed isomers)	Poison
95-80-7	2,4-Diaminotoluene	Poison
334-80-3	Diazomethane	Experimental tumorigen
132-64-9	Dibenzofuran	
96-12-8	1,2-Dibromo-3-chloropropane (DBCP)	Poison
106-93-4	1,2-Dibromoethane (Ethylene dibromide)	Poison
84-74-2	Dibutyl phthalate	Moderately toxic
25321-22-6	Dichlorobenzene (mixed isomers)	Poison
95-50-1	1,2-Dichlorobenzene	Poison
541-73-1	1,3-Dichlorobenzene	Poison
106-46-7	1,4-Dichlorobenzene	Poison
91-94-1	3,3-Dichlorobenzidine	Experimental carcinogen
75-27-4	Dichlorobromomethane	Moderately toxic
107-06-2	1,2-Dichloroethane	Poison

CAS NUMBER	CHEMICAL NAME	HAZARDS
540-59-0	1,2-Dichloroethylene	Poison
75-09-2	Dichloromethane (Methylene chloride)	Poison
120-83-2	2,4-Dichlorophenol	Poison
78-87-5	1,2-Dichloropropane	Moderately toxic
542-75-6	1,3-Dichloropropylene	Poison
62-73-7	Dichlorvos	Poison
115-32-2	Dicofol	Poison
1464-53-5	Diepoxybutane	Poison
111-42-2	Diethanolamine	Moderately toxic
117-81-7	di-(2-ethylhexyl) phthalate (DEHP)	Poison
84-66-2	Diethyl phthalate	Poison
64-67-5	Diethyl sulfate	Poison
119-90-4	3,3-Dimethoxybenzidine	Moderately toxic
60-11-7	4-Dimethylaminoazobenzene	Poison
119-93-7	3,3-Dimethylbenzidine (o-Tolidine)	Poison
79-44-7	Dimethylcarbamyl chloride	Poison
57-14-7	1,1-Dimethyl hydrazine	Poison
105-67-9	2,4-Dimethylphenol	Poison
131-11-3	Dimethyl phthalate	Moderately toxic
77-78-1	Dimethyl sulfate	Poison
534-52-1	4,6-Dinitro-o-cresol	Poison
51-28-5	2,4-Dinitrophenol	Deadly poison
121-14-2	2,4-Dinitrotoluene	Poison
606-20-2	2,5-Dinitrotoluene	Moderately toxic
117-84-0	n-Dioctyl phthalate	Mildly toxic
123-91-1	1,4-Dioxane	Poison
122-66-7	1,2-Diphenylhydrazine (Hydrazobenzene)	Poison
106-89-8	Epichlorohydrin	Poison
110-80-5	2-Ethoxyethanol	Moderately toxic
140-88-5	Ethyl acrylate	Poison
100-41-4	Ethylbenzene	Moderately toxic
541-41-3	Ethyl chloroformate	Poison
74-85-1	Ethylene	Simple asphyxiant
107-21-1	Ethylene glycol	Poison
151-56-4	Ethyleneimine (Aziridine)	Poison
75-21-8	Ethylene oxide	Poison
96-45-7	Ethylene thiourea	Poison
2164-17-2	Fluometuron	Poison
50-00-0	Formaldehyde	Poison
76-13-1	Freon 113	Mildly toxic
76-44-8	Heptachlor (1,4,5,6,7,8,8,-Heptachloro-3a,4,7,7a-tetrahydro-4,7-methano-1H-indene)	Poison
118-74-1	Hexachlorobenzene	Poison
87-68-3	Hexachloro-1,3-butadiene	Poison
77-47-4	Hexachlorocyclopentadiene	Deadly poison
67-72-1	Hexachloroethane	Poison
13355-87-1	Hexachloronaphthalene	Poison
680-31-9	Hexamethylphosphoramide	Experimental carcinogen
302-01-2	Hydrazine	Poison
10034-93-2	Hydrazine sulfate	Poison
7647-01-0	Hydrochloric acid	Poison
74-90-8	Hydrogen cyanide	Deadly poison
7664-39-3	Hydrogen fluoride	Poison
123-31-9	Hydroquinone	Poison
78-84-2	Isobutyraldehyde	Moderately toxic
67-63-0	Isopropyl alcohol	Poison
80-05-7	4,4-Isopropylidenediphenol	Poison
7439-92-1	Lead	Poison
58-89-9	Lindene	Poison
108-31-6	Maleic acid	Poison
12427-38-2	Maneb	Experimental carcinogen
7439-96-5	Manganese	Experimental tumorigen
108-78-1	Melamine	Experimental carcinogen

CAS NUMBER	CHEMICAL NAME	HAZARDS
7439-97-6	Mercury	Poison
67-56-1	Methanol	Poison
72-43-5	Methoxychlor (Benzene-1,1-(2,2,2,-trichloroethylidene)bis(4-methoxy)	Moderately toxic
109-86-4	2-Methoxyethanol	Moderately toxic
96-33-3	Methyl acrylate	Poison
1634-04-4	Methyl tert-butyl ether	Flammable
101-14-4	4,4-Methylenebis(2-chloro aniline)	Poison
101-61-1	4,4-Methylenebis (N,N-dimethyl)benzenamine	Moderately toxic
101-68-8	Methylenebis(phenylisocyanate)	Poison
74-95-3	Methylene bromide	Poison
101-77-9	4,4-Methylenedianiline	Poison
78-93-3	Methyl ethyl ketone	Moderately toxic
60-34-4	Methyl hydrazine	Poison
74-88-4	Methyl iodide	Poison
108-10-1	Methyl isobutyl ketone	Poison
624-83-9	Methyl isocyanate	Poison
80-62-6	Mehtyl methacrylate	Moderately toxic
90-94-8	Michler’s ketone	Poison
1313-27-5	Molybdenum trioxide	Poison
505-60-2	Mustard gas	Poison
91-20-3	Naphthalene	Poison
134-32-7	alpha-Naphthylamine	Poison
91-59-8	beta-Naphthylamine	Poison
7440-02-0	Nickel	Poison
7697-37-2	Nitric acid	Poison
139-13-9	Nitrilotriacetic acid	Poison
99-59-2	5-Nitro-o-anisidine	Moderately toxic
98-95-3	Nitrobenzene	Poison
92-93-3	4-Nitrobephenyl	Poison
1836-75-5	Nitrofen	Poison
51-75-2	Nitrogen mustard	Deadly poison
55-63-0	Nitroglycerin	Poison
88-75-5	2-Nitrophenol	Poison
100-02-7	4-Nitrophenol	Poison
79-46-9	2-Nitropropane	Poison
156-10-5	p-Nitrosodiphenylamine	Poison
121-69-7	N,N,-Dimethylaniline	Poison
924-16-3	N-Nitrosodi-n-butylamine	Moderately toxic
55-18-5	N-Nitrosodiethylamine	Poison
62-75-9	N-Nitrosodimethylamine	Poison
86-30-6	N-Nitrosodiohenylamine	Moderately toxic
621-64-7	N-Nitrosodi-n-propylamine	Moderately toxic
4549-40-0	N-Nitrosomethylvinylamine	Poison
59-89-2	N-Nitrosomorpholine	Poison
759-73-9	N-Nitroso-N-ethylurea	Poison
684-93-5	N-Nitroso-N-methylurea	Poison
16543-55-8	N-Nitrosonorrnicotine	Experimental carcinogen
100-75-4	N-Nitrosopiperidine	Poison
2234-13-1	Octachloronaphthlene	Poison
20816-12-0	Osmiun tetroxide	Poison
56-38-2	Parathion	Deadly poison
87-86-5	Pentachlorophenol	Poison
79-21-0	Peracetic acid	Poison
108-95-2	Phenol	Poison
106-50-3	p-Phenylenediamine	Poison
90-43-7	2-Phenylphenol	Poison
75-44-5	Phosgene	Poison
7664-38-2	Phosphoric acid	Poison
7723-14-0	Phosphorus	Poison
85-44-9	Phthalic anhydride	Poison
88-89-1	Picric acid	Poison

CAS NUMBER	CHEMICAL NAME	HAZARDS
1336-36-3	Polychlorinated biphenyls (PCBs)	Moderately toxic
1120-71-4	Propane sultone	Poison
57-57-8	beta-Propiolactone	Poison

123-38-6	Propionaldehyde	Moderately toxic
114-26-1	Propoxur	Poison
115-07-1	Propylene (propene)	Simple asphyxiant
75-55-8	Propyleneimine	Poison
75-56-9	Propylene oxide	Poison
110-86-1	Pyridine	Poison
91-22-5	Quinoline	Poison
106-51-4	Quinone	Poison
82-68-8	Quintozene (Pentachloronitrobenzene)	Experimental carcinogen
81-07-2	Saccharin	Moderately toxic
94-59-7	Safrole	Poison
7782-49-2	Selenium	Poison
7440-22-4	Silver	Experimental tumorigen
1310-73-2	Sodium hydroxide (solution)	Poison
7757-82-6	Sodium sulfate (solution)	Moderately toxic
100-42-5	Styrene	Experimental poison
96-09-3	Styrene oxide	Moderately toxic
7664-93-9	Sulfuric acid	Poison
100-21-0	Terephthalic acid	Moderately toxic
79-34-5	1,1,2,2,-Tetrachloroethane	Poison
127-18-4	Tetrachloroethylene	Experimental poison
961-11-5	Tetrachlorovinphos	Poison
7440-28-0	Thallium	Poison
62-55-5	Thioacetamide	Poison
139-65-1	4,4-Thiodianiline	Poison
62-56-6	Thiourea	Poison
1314-20-1	Thorium dioxide	Carcinogen
7550-45-0	Titanium tetrachloride	Poison
108-88-3	Toluene	Poison
584-84-9	Toulene-2,4-diisocyanate	Poison
91-08-7	Toluene-2,6-diisocyanate	Poison
95-53-4	o-Toluidine	Poison
636-21-5	o-Toluidine hydrochloride	Poison
8001-35-2	Toxaphene	Poison
68-76-8	Triaziquone	Poison
52-68-6	Trichlorfon (Phosphoric acid (2,2,2-trichloro-1-hydroxyethyl)-dimethyl ester	Poison
120-82-1	1,2,4-Trichlorobenzene	Poison
71-55-6	1,1,1-Trichloroethane (methyl chloroform)	Poison
79-00-5	1,1,2-Trichloroethane	Poison
79-01-6	Trichloroethylene	Experimental poison
95-95-4	2,4,5-Trichlorophenol	Poison
88-06-2	2,4,6-Trichlorophenol	Poison
1582-09-8	Trifluralin	Moderately toxic
95-63-6	1,2,4-Trimethylbenzene	Moderately toxic
126-72-7	Tris(2,3-dibromopropyl) phosphate	Poison
51-79-6	Urethane (Ethyl carbamate)	Moderately toxic
7440-62-2	Vanadium (fume or dust)	Poison
108-05-4	Vinyl acetate	Moderately toxic
593-60-2	Vinyl bromide	Moderately toxic
75-01-4	Vinyl chloride	Poison
75-35-4	Vinylidene chloride	Poison
1330-20-7	Xylene (mixed isomers)	Moderately toxic
108-38-3	m-Xylene	Moderately toxic
95-47-6	o-Xylene	Moderately toxic
106-42-3	p-Xylene	Moderately toxic
87-62-7	2,6-Xylidine	Moderately toxic
7440-66-6	Zinc (fume or dust)	Skin & systemic irritant
12122-67-7	Zineb	Moderately toxic

Chapter 12
Induced Damage Methods - Debris

12.1 Introduction

Very little has been done in the area of estimating debris from earthquakes. Some of the early regional loss estimation studies (e.g., Algermissen, et al., 1973; Rogers, et al., 1976) included some simplified models for estimating the amount of debris from shaking damage to unreinforced masonry structures. This methodology adopts a similar empirical approach to estimate two different types of debris. The first is debris that falls in large pieces, such as steel members or reinforced concrete elements. These require special treatment to break into smaller pieces before they are hauled away. The second type of debris is smaller and more easily moved with bulldozers and other machinery and tools. This includes brick, wood, glass, building contents and other materials. The methodology highlighting the Debris component is shown in Flowchart 12.1.

12.1.1 Scope

The module will estimate debris from building damage during earthquakes. No debris estimates are made for bridges or other lifelines.

12.1.2 Form of Damage Estimate

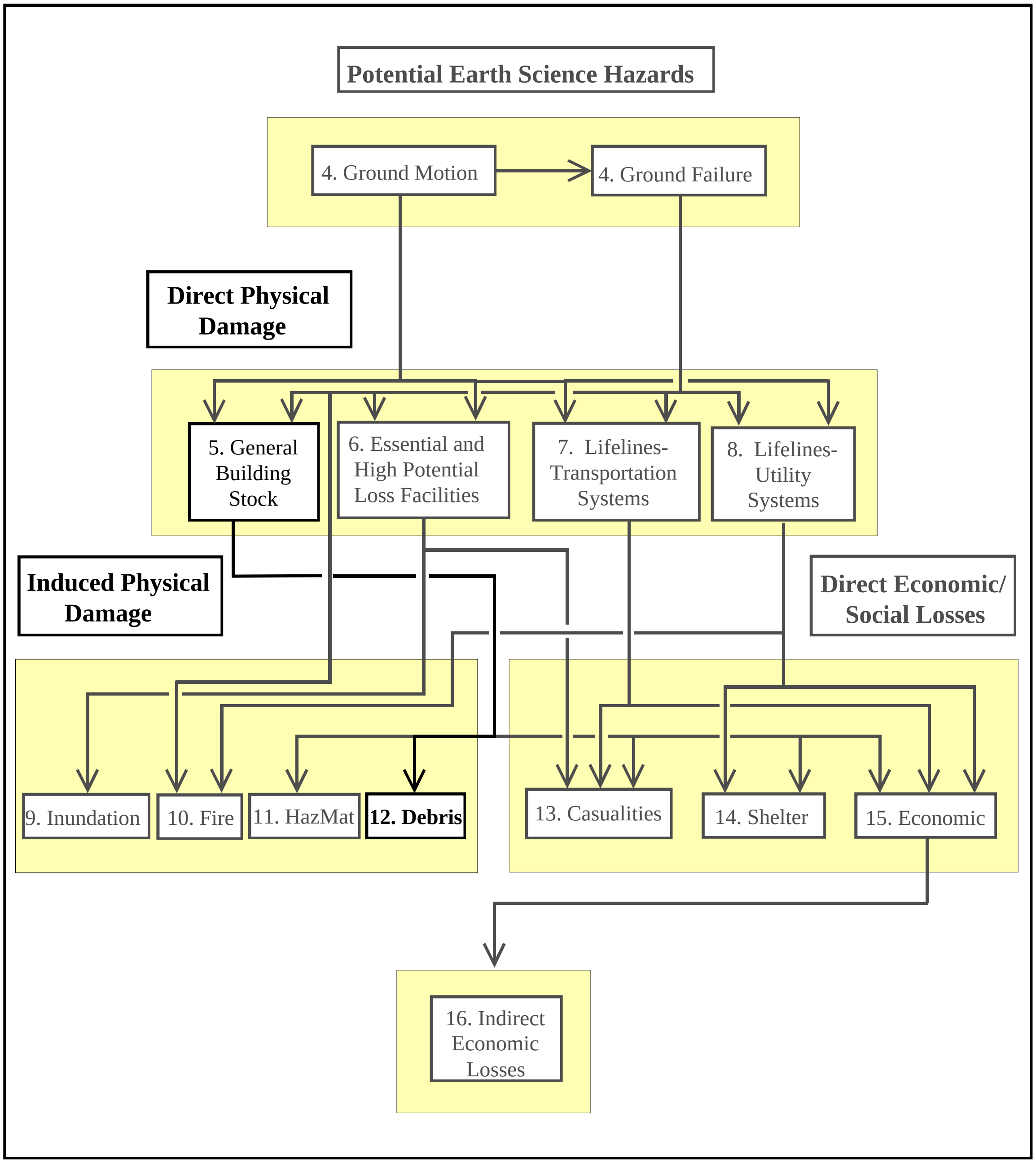
The module will determine the expected amounts of debris to be generated for each census tract. Output from this module will be the weight (tons) of debris. The classes of debris are defined as follows:

- Brick, wood and other
- Reinforced concrete and steel members

12.1.3 Input Requirements and Output Information

Input to this module includes the following items:

- Probabilities of structural and nonstructural damage states for model building types for each census tract provided from the direct physical damage module
- Square footage by occupancy class for each census tract provided from the inventory
- The occupancy to model building type relationship for each census tract



Flowchart 12.1: Debris Component Relationship to other Modules of the Earthquake Loss Estimation Methodology

12.2 Description of Methodology

The methodology for debris estimation is an empirical approach. That is, given the damage states for structural and nonstructural components, debris estimates are based on observations of damage that has occurred in past earthquakes and estimates of the weights of structural and nonstructural elements. The estimation can be made considering model building type, general occupancy class or specific occupancy class. In this section, the methodology described is based on model building types. Tables have been compiled to estimate generated debris from different structural and nonstructural damage states for each model building type. Given the distribution of different building types in square footage in each occupancy class, similar tables can also be compiled to estimate debris based on occupancy class.

12.2.1 Debris Generated From Damaged Buildings

Debris generated from damaged buildings (in tons) is based on the following factors:

- Unit weight of structural and nonstructural elements (tons per 1000 sq. ft. of floor area) for each of the model building types
- Probabilities of damage states for both structural and drift-sensitive nonstructural elements by census tract
- Square footage of each of the model building types by census tract
- Debris generated from different damage states of structural and nonstructural elements (% of unit weight of element)

The recommended values for unit weights of structural and nonstructural elements and debris generated per model building type are given in Tables 12.1, 12.2 and 12.3.

Table 12.1 Unit Weight (tons per 1000 ft^2) for Structural and Nonstructural Elements for the Model Building Types

#	Model Building Type	Brick, Wood and Other		Reinforced Concrete and Steel	
		Structural	Nonstructural	Structural	Nonstructural
1	W1	6.5	12.1	15.0	0.0
2	W2	4.0	8.1	15.0	1.0
3	S1L	0.0	5.3	44.0	5.0
4	S1M	0.0	5.3	44.0	5.0
5	S1H	0.0	5.3	44.0	5.0
6	S2L	0.0	5.3	44.0	5.0
7	S2M	0.0	5.3	44.0	5.0
8	S2H	0.0	5.3	44.0	5.0
9	S3	0.0	0.0	67.0	1.5
10	S4L	0.0	5.3	65.0	4.0
11	S4M	0.0	5.3	65.0	4.0
12	S4H	0.0	5.3	65.0	4.0
13	S5L	20.0	5.3	45.0	4.0
14	S5M	20.0	5.3	45.0	4.0
15	S5H	20.0	5.3	45.0	4.0
16	C1L	0.0	5.3	98.0	4.0
17	C1M	0.0	5.3	98.0	4.0
18	C1H	0.0	5.3	98.0	4.0
19	C2L	0.0	5.3	112.0	4.0
20	C2M	0.0	5.3	112.0	4.0
21	C2H	0.0	5.3	112.0	4.0
22	C3L	20.0	5.3	90.0	4.0
23	C3M	20.0	5.3	90.0	4.0
24	C3H	20.0	5.3	90.0	4.0
25	PC1	5.5	5.3	40.0	1.5
26	PC2L	0.0	5.3	100.0	4.0
27	PC2M	0.0	5.3	100.0	4.0
28	PC2H	0.0	5.3	100.0	4.0
29	RM1L	17.5	5.3	28.0	4.0
30	RM1M	17.5	5.3	28.0	4.0
31	RM2L	17.5	5.3	78.0	4.0
32	RM2M	24.5	5.3	78.0	4.0
33	RM2H	24.5	5.3	78.0	4.0
34	URML	35.0	10.5	41.0	4.0
35	URMM	35.0	10.5	41.0	4.0
36	MH	10.0	18.0	22.0	0.0

Table 12.2 Brick, Wood, and Other Debris Generated from Damaged Structural and Nonstructural Elements (in Fraction of Weight, %)

#	Building Type	Structural Damage State				Nonstructural Damage State			
		Slight	Moder	Exten	Comp	Slight	Moder	Exten	Comp
1	W1	0.0	5.0	34.0	100.0	2.0	8.0	35.0	100.0
2	W2	0.0	6.0	33.0	100.0	2.0	10.0	40.0	100.0
3	S1L	0.0	0.0	0.0	100.0	1.0	7.0	35.0	100.0
4	S1M	0.0	0.0	0.0	100.0	1.0	7.0	35.0	100.0
5	S1H	0.0	0.0	0.0	100.0	1.0	7.0	35.0	100.0
6	S2L	0.0	0.0	0.0	100.0	0.0	0.0	0.0	100.0
7	S2M	0.0	0.0	0.0	100.0	0.0	0.0	0.0	100.0
8	S2H	0.0	0.0	0.0	100.0	0.0	0.0	0.0	100.0
9	S3	0.0	0.0	0.0	100.0	0.0	0.0	0.0	100.0
10	S4L	0.0	0.0	0.0	100.0	1.0	7.0	35.0	100.0
11	S4M	0.0	0.0	0.0	100.0	1.0	7.0	35.0	100.0
12	S4H	0.0	0.0	0.0	100.0	1.0	7.0	35.0	100.0
13	S5L	5.0	25.0	60.0	100.0	1.0	7.0	35.0	100.0
14	S5M	5.0	25.0	60.0	100.0	1.0	7.0	35.0	100.0
15	S5H	5.0	25.0	60.0	100.0	1.0	7.0	35.0	100.0
16	C1L	0.0	0.0	0.0	100.0	1.0	7.0	35.0	100.0
17	C1M	0.0	0.0	0.0	100.0	1.0	7.0	35.0	100.0
18	C1H	0.0	0.0	0.0	100.0	1.0	7.0	35.0	100.0
19	C2L	0.0	0.0	0.0	100.0	1.0	7.0	35.0	100.0
20	C2M	0.0	0.0	0.0	100.0	1.0	7.0	35.0	100.0
21	C2H	0.0	0.0	0.0	100.0	1.0	7.0	35.0	100.0
22	C3L	5.0	25.0	60.0	100.0	1.0	7.0	35.0	100.0
23	C3M	5.0	25.0	60.0	100.0	1.0	7.0	35.0	100.0
24	C3H	5.0	25.0	60.0	100.0	1.0	7.0	35.0	100.0
25	PC1	0.0	6.0	32.0	100.0	2.0	11.0	42.0	100.0
26	PC2L	0.0	0.0	0.0	100.0	1.0	7.0	35.0	100.0
27	PC2M	0.0	0.0	0.0	100.0	1.0	7.0	35.0	100.0
28	PC2H	0.0	0.0	0.0	100.0	1.0	7.0	35.0	100.0
29	RM1L	3.5	20.0	50.0	100.0	2.0	10.0	40.0	100.0
30	RM1M	3.5	20.0	50.0	100.0	2.0	10.0	40.0	100.0
31	RM2L	5.0	25.0	60.0	100.0	1.0	7.0	35.0	100.0
32	RM2M	5.0	25.0	60.0	100.0	1.0	7.0	35.0	100.0
33	RM2H	5.0	25.0	60.0	100.0	1.0	7.0	35.0	100.0
34	URML	5.0	25.0	55.0	100.0	2.0	12.0	45.0	100.0
35	URMM	5.0	25.0	55.0	100.0	2.0	12.0	45.0	100.0
36	MH	0.0	5.0	33.0	100.0	2.0	8.0	35.0	100.0

Table 12.3 Reinforced Concrete and Wrecked Steel Generated from Damaged Structural and Nonstructural Elements (in Percentage of Weight)

#	Building Type	Structural Damage State				Nonstructural Damage State			
		Slight	Moder	Exten	Comp	Slight	Moder	Exten	Comp
1	W1	0.0	3.0	27.0	100.0	0.0	0.0	0.0	100.0
2	W2	0.0	2.0	25.0	100.0	0.0	10.0	28.0	100.0
3	S1L	0.0	4.0	30.0	100.0	0.1	8.0	28.0	100.0
4	S1M	0.0	4.0	30.0	100.0	0.1	8.0	28.0	100.0
5	S1H	0.0	4.0	30.0	100.0	0.1	8.0	28.0	100.0
6	S2L	0.0	4.0	30.0	100.0	0.1	8.0	28.0	100.0
7	S2M	0.0	4.0	30.0	100.0	0.1	8.0	28.0	100.0
8	S2H	0.0	4.0	30.0	100.0	0.1	8.0	28.0	100.0
9	S3	0.0	5.0	30.0	100.0	0.0	10.0	30.0	100.0
10	S4L	2.0	10.0	40.0	100.0	0.1	10.0	30.0	100.0
11	S4M	2.0	10.0	40.0	100.0	0.1	10.0	30.0	100.0
12	S4H	2.0	10.0	40.0	100.0	0.1	10.0	30.0	100.0
13	S5L	0.0	4.0	30.0	100.0	0.1	10.0	30.0	100.0
14	S5M	0.0	4.0	30.0	100.0	0.1	10.0	30.0	100.0
15	S5H	0.0	4.0	30.0	100.0	0.1	10.0	30.0	100.0
16	C1L	0.0	5.0	33.0	100.0	0.1	8.0	28.0	100.0
17	C1M	0.0	5.0	33.0	100.0	0.1	8.0	28.0	100.0
18	C1H	0.0	5.0	33.0	100.0	0.1	8.0	28.0	100.0
19	C2L	1.0	8.0	35.0	100.0	0.1	10.0	30.0	100.0
20	C2M	1.0	8.0	35.0	100.0	0.1	10.0	30.0	100.0
21	C2H	1.0	8.0	35.0	100.0	0.1	10.0	30.0	100.0
22	C3L	0.0	4.0	32.0	100.0	0.1	10.0	30.0	100.0
23	C3M	0.0	4.0	32.0	100.0	0.1	10.0	30.0	100.0
24	C3H	0.0	4.0	32.0	100.0	0.1	10.0	30.0	100.0
25	PC1	2.0	10.0	35.0	100.0	0.1	10.0	30.0	100.0
26	PC2L	2.0	7.0	35.0	100.0	0.1	9.0	30.0	100.0
27	PC2M	2.0	7.0	35.0	100.0	0.1	9.0	30.0	100.0
28	PC2H	2.0	7.0	35.0	100.0	0.1	9.0	30.0	100.0
29	RM1L	0.0	3.0	25.0	100.0	0.1	10.0	30.0	100.0
30	RM1M	0.0	3.0	25.5	100.0	0.1	10.0	31.0	100.0
31	RM2L	0.0	3.0	30.5	100.0	0.1	9.0	30.0	100.0
32	RM2M	0.0	3.0	30.5	100.0	0.1	9.0	30.0	100.0
33	RM2H	0.0	3.0	30.5	100.0	0.1	9.0	30.0	100.0
34	URML	0.0	2.0	25.0	100.0	0.0	10.0	29.0	100.0
35	URMM	0.0	2.0	25.0	100.0	0.0	10.0	29.0	100.0
36	MH	0.0	3.0	27.0	100.0	0.0	0.0	0.0	100.0

The following notation is used throughout the chapter.

i - the iteration variable for the types of debris, i = 1 to 2

where: 1- brick, wood and other

2- reinforced concrete and steel components

j - the iteration variable for the damage states, j=1 to 5,

where: 1- none, 2- slight; 3- moderate; 4- extensive; 5- complete

k - the iteration variable for the model building types, k=1 to 36

The inputs provided from direct physical damage module are the probabilities of different structural and nonstructural damage states. Thus, the first step in the debris calculation is to combine the debris fraction generated from the different damage states into the expected debris fraction for each model building type. The expected debris fraction for model building type k and debris type i due to structural damage is given by:

$$EDF_s(i,k)=\sum_{j=2}^{5} P_s(j,k)*DF_s(i,j,k) \tag{12-1}$$

where:

$EDF_s(i,k)$ - the expected debris fraction of debris type i due to structural damage for model building type k

$P_s(j,k)$ - the probability of structural damage state j for model building type k at the location being considered

$DF_s(i,j,k)$ - the debris fraction of debris type i for model building type k in structural damage state j (from Tables 12.2 and 12.3)

The expected debris fraction of debris type i due to nonstructural damage is given by:

$$EDF_{ns}(i,k)=\sum_{j=2}^{5} P_{ns}(j,k)*DF_{ns}(i,j,k) \tag{12-2}$$

where:

$EDF_{ns}(i,k)$ - the expected debris fraction of debris type i due to nonstructural damage for model building type k

$P_{ns}(j,k)$ - the probability of drift sensitive nonstructural damage state j for model building type k at the location being considered

$DF_{ns}(i,j,k)$ - the debris fraction of debris type i for model building type k in drift sensitive nonstructural damage state j (from Tables 12.2 and 12.3)

These values indicate the expected percentage of debris type i generated due to structural or nonstructural damage to model building type k. If we know the square footage of each model building type (by census tract), SQ(k), and weights of debris type i per 1000 ft^2 of building, $W_s(i,k)$ and $W_{ns}(i,k)$, then the amount of debris for this particular location can be obtained as follows:

$$DB(i) = \sum_{k=1}^{36} \left[EDF_s(i,k) * W_s(i,k) + EDF_{ns}(i,k) * \cdot W_{ns}(i,k) \right] * SQ(k) \qquad (12\text{-}3)$$

where:

- $W_s(i,k)$ - the weight of debris type i per 1000 ft^2 of floor area for structural elements of model building type k (From Table 12.1)
- $W_{ns}(i,k)$ - the weight of debris type i per 1000 ft^2 of floor area for nonstructural elements of model building type k; (From Table 12.1)
- $SQ(k)$ - the census tract square footage for model building type k in thousands of square feet
- $DB(i)$ - the amount of debris type i (in tons)

12.3 Guidance for Expert-Generated Estimates

There is no difference in the methodology for Advanced Data and Models Analysis except more accurate input.

12.4 References

Algermissen, S. T., M. Hopper, K. Campbell, W. A. Rinehart, D. Perkins, K. V. Steinbrugge, H. J. Lagorio, D. F. Moran, F. S. Cluff, H. J. Degenkolb, C. M. Duke, G. O. Gates, N. N. Jacobson, R. A. Olson, and C. R. Allen. 1973. "A Study of Earthquake Losses in the Los Angeles, California Area." Washington, D.C.: National Oceanic and Atmospheric Administration (NOAA).

Rogers, A. M., S. T. Algermissen, W. W. Hays, D. M. Perkins, D. O. Van Strien, H. C. Hughes, R. C. Hughes, H. J. Lagorio, and K. V. Steinbrugge. 1976. "A Study of Earthquake Losses in the Salt Lake City, Utah Area" - USGS OFR 76-89. Washington, D.C.: United States Geological Survey.

Chapter 13
Direct Social Losses - Casualties

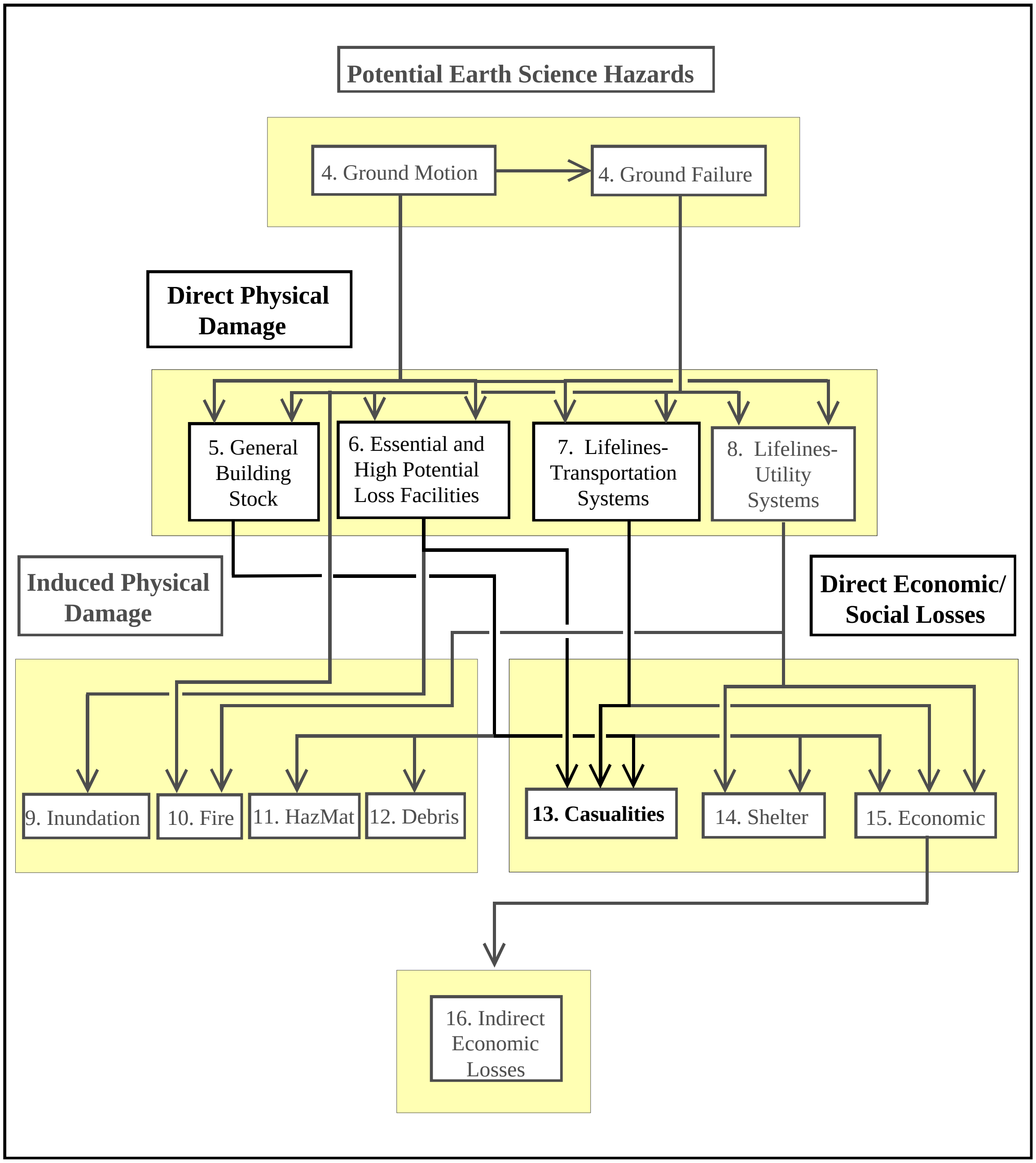
13.1 Introduction

This chapter describes and develops the methodology for the estimation of casualties, describes the form of output, and defines the required input. The methodology is based on the assumption that there is a strong correlation between building damage (both structural and nonstructural) and the number and severity of casualties. In smaller earthquakes, nonstructural damage will most likely control the casualty estimates. In severe earthquakes where there will be a large number of collapses and partial collapses, there will be a proportionately larger number of fatalities. Data regarding earthquake related injuries are not of the best quality. Data are not available across all model building types. Available data often have insufficient information about the type of structure in which the casualties occurred and the casualty generating mechanism. Thus an attempt to develop very sophisticated models based on such data is neither feasible nor reliable. The methodology highlighting the Casualty component is shown in Flowchart 13.1.

13.1.1 Scope

This module provides a methodology for estimating casualties caused only by building and bridge damage. The model estimates casualties directly caused by structural or non-structural damage although non-structural casualties are not directly derived from non-structutral damage but instead are derived from structural damage output. The method excludes casualties caused by heart attacks, car accidents, falls, power failure which causes failure of a respirator, incidents during post-earthquake search and rescue or post-earthquake clean-up and construction activities, electrocution, tsunami, landslides, liquefaction, fault rupture, dam failures, fires or hazardous materials releases. Psychological impacts of the earthquake on the exposed population are not modeled. A study by Aroni and Durkin (1985) suggests that falls would add to the injuries estimate. Studies by Durkin (1992, 1995) suggest that falls, heart attacks, car accidents, fire and other causes not directly attributable to structural or nonstructural damage would increase estimates of deaths.

Although fire following earthquakes has been the cause of significant casualties (notably in the firestorm following the 1923 Kanto, Japan, earthquake), such cases have involved the combination of a number of conditions, which are of low probability of occurrence in U.S. earthquakes. More typical of fires in the U.S is the catastrophic Oakland Hills fire of 1990, in which over 3500 residences were destroyed, yet casualties were low. Similarly, there is the possibility (but low probability) of a large number of casualties due to tsunami, landslides, sudden failure of a critical dam, or a massive release of toxic substances. If the particular characteristics of the study region give the user cause for concern about the possibility of casualties from fire, tsunami, landslides, liquefaction, dam failure, or hazardous materials, it would be advisable to initiate specific studies directed towards the problem.



Flowchart 13.1: Direct Social Loss (Casualties) Relationship to other Components of the Earthquake Loss Estimation Methodology

The scope of this module is to provide a simple and consistent framework for earthquake casualty estimation and formats for data collection and data sharing across the disciplines that are involved in casualty estimation. Many recognized relevant issues in casualty estimation such as occupancy potential, collapse and non-collapse vulnerability of the building stock, time of the earthquake occurrence, and spatial distribution of the damage, are included in the methodology. The methodology is flexible enough to handle:

- United States-specific casualty data when available
- Data based on interpretation of worldwide casualty data for casualty estimations in the United States
- Multidisciplinary inputs from engineering, medical, social science, and other disciplines involved with earthquake related casualty estimation.

Data formats are flexible enough to handle currently available data, to re-evaluate previously collected data, and to accept new data as they become available.

13.1.2 Form of Casualty Estimate

The output from the module consists of a casualty breakdown by injury severity level, defined by a four level injury severity scale (Durkin and Thiel, 1991; Coburn, 1992; Cheu, 1994). Casualties are calculated at the census tract level. The output is at the census tract level and aggregated to the study region. Table 13.1 defines the injury classification scale used in the methodology.

Table 13.1: Injury Classification Scale

Injury Severity Level	Injury Description
Severity 1	Injuries requiring basic medical aid that could be administered by paraprofessionals. These types of injuries would require bandages or observation. Some examples are: a sprain, a severe cut requiring stitches, a minor burn (first degree or second degree on a small part of the body), or a bump on the head without loss of consciousness. Injuries of lesser severity that could be self treated are not estimated by Hazus.
Severity 2	Injuries requiring a greater degree of medical care and use of medical technology such as x-rays or surgery, but not expected to progress to a life threatening status. Some examples are third degree burns or second degree burns over large parts of the body, a bump on the head that causes loss of consciousness, fractured bone, dehydration or exposure.
Severity 3	Injuries that pose an immediate life threatening condition if not treated adequately and expeditiously. Some examples are: uncontrolled bleeding, punctured organ, other internal injuries, spinal column injuries, or crush syndrome.
Severity 4	Instantaneously killed or mortally injured

Other, more elaborate casualty scales exist. They are based on quantifiable medical parameters such as medical injury severity scores, coded physiologic variables, and other factors. The selected four-level injury scale represents an achievable compromise between the demands of the medical community (in order to plan their response), and the ability of the engineering community to provide the required data. For example, medical professionals would like to have the classification in terms of "Injuries/Illnesses" to account for worsened medical conditions caused by an earthquake (e.g., heart attack). However, currently available casualty assessment methodologies do not allow for a finer resolution in the casualty scale definition.

13.1.3 Input Requirements

There are three types of data used by the casualty module:

- Scenario time definition
- Data supplied by other modules
- Data specific to the casualty module

Scenario Time Definition

The methodology provides information necessary to produce casualty estimates for three times of day. The following time options are provided:

- Earthquake striking at 2:00 a.m. (night time scenario)
- Earthquake striking at 2:00 p.m. (day time scenario)
- Earthquake striking at 5:00 p.m. (commute time scenario)

These scenarios are expected to generate the highest casualties for the population at home, the population at work/school and the population during rush hour, respectively.

Data Supplied by Other Modules

Other modules supply population distribution data, inventory (building stock distribution) data, and damage state probabilities. These data are provided at the census tract level. The default values provided in the methodology are best estimates, made from available data. However, it is fully expected that the user will modify the default database contingent on the availability of improved information.

Population Distribution Data

The population for each census tract is distributed into six basic groups:

- Residential population
- Commercial population
- Educational population
- Industrial population
- Commuting population
- Hotel population

The default population distribution is calculated for the three times of day for each census tract. Table 13.2 provides the relationships used to determine the default distribution. There are two multipliers associated with each entry in the table. The second multiplier indicates the fraction of a population component present in an occupancy for a particular scenario time. The first multiplier then divides that population component into indoors and outdoors. For example at 2 AM, the default is that 99% (0.99) of the nighttime residential population will be in a residential occupancy and 99.9% (0.999) of those people will be indoors. These factors should be changed if better information is available.

The factor of 0.80 that is multiplied by the number of children aged 16 and under, used to calculate educational population, is intended to represent the fact that children under the age of five are too young to go to school and that on any given day a certain number of students will not be attending school due to illness or other factors. Average attendance figures for public and private schools should be used when modifying the educational occupancy values in Table 13.2.

The population distribution is inferred from Bureau of the Census data and Dun and Bradstreet data and has an inherent error associated with the distribution. For example, the number of people in any given census tract at 5 PM is inferred from knowledge of where people work, where they live and travel times. Similarly, it is assumed that the children ages 16 and under are attending school in the census tract where they live. In many cases the user has a better understanding of the distribution of the working and school populations among census tracts. In this case, modifications to the default information should be made to reflect the improved knowledge. It is likely that improved information on the number of hotel visitors can be obtained from the local visitors bureau.

Table 13.2: Default Relationships for Estimating Population Distribution

Distribution of People in Census Tract			
Occupancy	**2:00 a.m.**	**2:00 p.m.**	**5:00 p.m.**
Indoors			
Residential	(0.999)0.99(NRES)	(0.70)0.75(DRES)	(0.70)0.5(NRES)
Commercial	(0.999)0.02(COMW)	(0.99)0.98(COMW) + (0.80)0.20(DRES) + 0.80(HOTEL) + 0.80(VISIT)	0.98[0.50(COMW) + 0.10(NRES)+ 0.70(HOTEL)]
Educational		(0.90)0.80(GRADE) + 0.80(COLLEGE)	(0.80)0.50(COLLEGE)
Industrial	(0.999)0.10(INDW)	(0.90)0.80(INDW)	(0.90)0.50(INDW)
Hotels	0.999(HOTEL)	0.19(HOTEL)	0.299(HOTEL)
Outdoors			
Residential	(0.001)0.99(NRES)	(0.30)0.75(DRES)	(0.30)0.5(NRES)
Commercial	(0.001)0.02(COMW)	(0.01)0.98(COMW) + (0.20)0.20(DRES) + (0.20)VISIT + 0.50(1-PRFIL)0.05(POP)	0.02[0.50(COMW) + 0.10(NRES) + 0.70(HOTEL)] + 0.50(1-PRFIL) [0.05(POP) + 1.0(COMM)]
Educational		(0.10)0.80(GRADE) + 0.20(COLLEGE)	(0.20)0.50(COLLEGE)
Industrial	(0.001)0.10(INDW)	(0.10)0.80(INDW)	(0.10)0.50(INDW)
Hotels	0.001(HOTEL)	0.01(HOTEL)	0.001(HOTEL)
Commuting			
Commuting in cars	0.005(POP)	(PRFIL)0.05(POP)	(PRFIL)[0.05(POP) + 1.0(COMM)]
Commuting using other modes		0.50(1-PRFIL)0.05(POP)	0.50(1-PRFIL) [0.05(POP) + 1.0(COMM)]

where:

POP	is the census tract population taken from census data
DRES	is the daytime residential population inferred from census data
NRES	is the nighttime residential population inferred from census data
COMM	is the number of people commuting inferred from census data
COMW	is the number of people employed in the commercial sector
INDW	is the number of people employed in the industrial sector
GRADE	is the number of students in grade schools (K-12)
COLLEGE	is the number of students on college and university campuses in the census tract
HOTEL	is the number of people staying in hotels in the census tract

PRFIL	is a factor representing the proportion of commuters using automobiles, inferred from profile of the community (0.60 for dense urban, 0.80 for less dense urban or suburban, and 0.85 for rural). The default is 0.80.
VISIT	is the number of regional residents who do not live in the study area, visiting the census tract for shopping and entertainment. Default is set to zero.

The commuting population is defined as the number of people expected in vehicles, public transit, riding bicycles and walking during the commuting time. In this methodology, the only roadway casualties estimated are those incurred from bridge/overpass damage. This requires the user to estimate the number of people located on or under bridges during the seismic event. The methodology provides for a user-defined Commuter Distribution Factor, CDF, that corresponds to the percentage of the commuting population located on or under bridges. The number of people on or under bridges in a census tract is then computed as follows.

$$NBRDG = CDF*\text{Commuter Population} \tag{13-1}$$

where:

NBRDG	Number of people on or under bridges in the census tract
CDF	Commuter Distribution Factor: Percent of commuters on or under bridges in census tract (Defaults: CDF = 0.01 day, CDF = 0.01 night and CDF = 0.02 commute time.)

The methodology defaults the CDF to assumed values of 0.01 during the day and night time and 0.02 for the commuting time. This value is based on the assumption that on a typical major urban freeway or highway, an overpass would occur about every two miles. Local data on the percentage of commuters on or under highway bridges would provide greater accuracy.

General Occupancy to Model Building Type Mapping

The model uses the relationship between the general occupancy classes and the model building type, which is calculated by combining the following relationships.

- Specific Occupancy to Model Building Type Relationship (Tables 3A.2 through 3A.21)
- General Occupancy to Specific Occupancy Relationship (Table 3.2)

Damage State Probabilities

The casualty model uses four structural damage states (slight, moderate, extensive, and complete) computed by the direct physical damage module as well as a subset of complete indication building collapse. For each census tract and each model building type, the probabilities of the structure being in each of the four damage states are required. In addition, bridge casualties are estimated using the probability of the complete structural damage state for bridges.

Data Specific to The Casualty Module

This module limits itself to the estimation of casualties that would be caused by damage to buildings and bridges. Excluded are casualties or health effects not attributable to immediate physical impact, such as heart attacks, psychological effects, toxic release, or injuries suffered during post-earthquake clean-up or construction activities. Exterior casualties caused from collapsing masonry parapets, pieces of bearing walls, nonstructural wall panels, or from falling signs and other appendages are estimated and provided as a separate output of the model (outdoor casualties). The casualty rates used in the methodology are relatively uniform across building types for a given damage level, with differentiation to account for types of construction that pose higher-than-average hazards at moderate damage levels (e.g., falling of pieces of unreinforced masonry) or at severe levels (e.g., complete collapse of heavy concrete construction as compared to complete collapse of wood frame construction). For example, indoor casualty rates at slight structural damage are the same for all model building types. This is because at low levels of structural damage casualties most likely would be caused by non-structural components or contents, which do not vary greatly with model building type.

Rates used in the ATC-13 method were evaluated and revised based on comparison with a limited amount of historical data. General data trends such as, 10 to 20 times as many non-hospitalized injures as hospitalized injuries occurred in the Northridge earthquake (Durkin, 1995) and the hospitalization rate (hospitalizations that did not result in death) for LA county of 1.56 per 100,000 was four times the fatality rate of 0.37 per 100,000 (Peek-Asa et al., 1998), were gathered from available data to provide guidance as to reasonable casualty rates. For several recent events, including the Northridge, Loma Prieta and Nisqually earthquakes, the casualties estimated by the methodology are a reasonable representation of the actual numbers observed.

The user should keep in mind the intended use of the casualty estimates: to forecast the approximate magnitude of injuries and fatalities. For example, an estimate that Severity 3 casualties are in the low hundreds, rather that several thousand, for a future event or an earthquake that has just occurred, is useful to regional emergency medical authorities. Of course, for an event that has just occurred, there is no substitute for rapid surveys to compile actual figures. Note, however, that "actual" casualty counts may still contain errors. Even for fatalities, data reported for actuals are revised in the weeks and months following the earthquake.

The following default casualty rates are defined by the methodology.

Indoor Casualty Rates - Structural Damage

- Casualty rates by model building type for slight, moderate, and extensive structural damage

- Casualty rates by model building type for complete structural damage without structural collapse
- Casualty rates by model building type for complete structural damage with structural collapse
- Collapse rates by model building type for complete structural damage state.

Outdoor Casualty Rates - Structural Damage

- Casualty rates by model building type for slight, moderate, extensive and complete structural damage

Commuter Casualty Rates - Bridge Damage

- Casualty rates by bridge for the complete damage state.

It should be noted that only a portion of the buildings in the complete damage state is considered to be collapsed. The collapse percentages for each model building type are given in Chapter 5 and summarized in Table 13.8. The percentages in Table 13.8 are the estimated proportions of building square footage in the complete damage state that have collapsed for each model building type. Tables 13.3 through 13.11 define the values for the default casualty module data.

Table 13.3: Indoor Casualty Rates by Model Building Type for Slight Structural Damage

#	Building Type	Casualty Severity Level			
		Severity 1 (%)	Severity 2 (%)	Severity 3 (%)	Severity 4 (%)
1	W1	0.05	0	0	0
2	W2	0.05	0	0	0
3	S1L	0.05	0	0	0
4	S1M	0.05	0	0	0
5	S1H	0.05	0	0	0
6	S2L	0.05	0	0	0
7	S2M	0.05	0	0	0
8	S2H	0.05	0	0	0
9	S3	0.05	0	0	0
10	S4L	0.05	0	0	0
11	S4M	0.05	0	0	0
12	S4H	0.05	0	0	0
13	S5L	0.05	0	0	0
14	S5M	0.05	0	0	0
15	S5H	0.05	0	0	0
16	C1L	0.05	0	0	0
17	C1M	0.05	0	0	0
18	C1H	0.05	0	0	0
19	C2L	0.05	0	0	0
20	C2M	0.05	0	0	0
21	C2H	0.05	0	0	0
22	C3L	0.05	0	0	0
23	C3M	0.05	0	0	0
24	C3H	0.05	0	0	0
25	PC1	0.05	0	0	0
26	PC2L	0.05	0	0	0
27	PC2M	0.05	0	0	0
28	PC2H	0.05	0	0	0
29	RM1L	0.05	0	0	0
30	RM1M	0.05	0	0	0
31	RM2L	0.05	0	0	0
32	RM2M	0.05	0	0	0
33	RM2H	0.05	0	0	0
34	URML	0.05	0	0	0
35	URMM	0.05	0	0	0
36	MH	0.05	0	0	0
B1	Major Bridge	N/A	N/A	N/A	N/A
B2	Continuous Bridge	N/A	N/A	N/A	N/A
B3	S.S. Bridge	N/A	N/A	N/A	N/A

Table 13.4: Indoor Casualty Rates by Model Building Type for Moderate Structural Damage

#	Building Type	Casualty Severity Level			
		Severity 1 (%)	Severity 2 (%)	Severity 3 (%)	Severity 4 (%)
1	W1	0.25	0.030	0	0
2	W2	0.20	0.025	0	0
3	S1L	0.20	0.025	0	0
4	S1M	0.20	0.025	0	0
5	S1H	0.20	0.025	0	0
6	S2L	0.20	0.025	0	0
7	S2M	0.20	0.025	0	0
8	S2H	0.20	0.025	0	0
9	S3	0.20	0.025	0	0
10	S4L	0.25	0.030	0	0
11	S4M	0.25	0.030	0	0
12	S4H	0.25	0.030	0	0
13	S5L	0.20	0.025	0	0
14	S5M	0.20	0.025	0	0
15	S5H	0.20	0.025	0	0
16	C1L	0.25	0.030	0	0
17	C1M	0.25	0.030	0	0
18	C1H	0.25	0.030	0	0
19	C2L	0.25	0.030	0	0
20	C2M	0.25	0.030	0	0
21	C2H	0.25	0.030	0	0
22	C3L	0.20	0.025	0	0
23	C3M	0.20	0.025	0	0
24	C3H	0.20	0.025	0	0
25	PC1	0.25	0.030	0	0
26	PC2L	0.25	0.030	0	0
27	PC2M	0.25	0.030	0	0
28	PC2H	0.25	0.030	0	0
29	RM1L	0.20	0.025	0	0
30	RM1M	0.20	0.025	0	0
31	RM2L	0.20	0.025	0	0
32	RM2M	0.20	0.025	0	0
33	RM2H	0.20	0.025	0	0
34	URML	0.35	0.400	0.001	0.001
35	URMM	0.35	0.400	0.001	0.001
36	MH	0.25	0.030	0	0
B1	Major Bridge	N/A	N/A	N/A	N/A
B2	Continuous Bridge	N/A	N/A	N/A	N/A
B3	S.S. Bridge	N/A	N/A	N/A	N/A

Table 13.5: Indoor Casualty Rates by Model Building Type for Extensive Structural Damage

#	Building Type	Casualty Severity Level			
		Severity 1 (%)	Severity 2 (%)	Severity 3 (%)	Severity 4 (%)
1	W1	1	0.1	0.001	0.001
2	W2	1	0.1	0.001	0.001
3	S1L	1	0.1	0.001	0.001
4	S1M	1	0.1	0.001	0.001
5	S1H	1	0.1	0.001	0.001
6	S2L	1	0.1	0.001	0.001
7	S2M	1	0.1	0.001	0.001
8	S2H	1	0.1	0.001	0.001
9	S3	1	0.1	0.001	0.001
10	S4L	1	0.1	0.001	0.001
11	S4M	1	0.1	0.001	0.001
12	S4H	1	0.1	0.001	0.001
13	S5L	1	0.1	0.001	0.001
14	S5M	1	0.1	0.001	0.001
15	S5H	1	0.1	0.001	0.001
16	C1L	1	0.1	0.001	0.001
17	C1M	1	0.1	0.001	0.001
18	C1H	1	0.1	0.001	0.001
19	C2L	1	0.1	0.001	0.001
20	C2M	1	0.1	0.001	0.001
21	C2H	1	0.1	0.001	0.001
22	C3L	1	0.1	0.001	0.001
23	C3M	1	0.1	0.001	0.001
24	C3H	1	0.1	0.001	0.001
25	PC1	1	0.1	0.001	0.001
26	PC2L	1	0.1	0.001	0.001
27	PC2M	1	0.1	0.001	0.001
28	PC2H	1	0.1	0.001	0.001
29	RM1L	1	0.1	0.001	0.001
30	RM1M	1	0.1	0.001	0.001
31	RM2L	1	0.1	0.001	0.001
32	RM2M	1	0.1	0.001	0.001
33	RM2H	1	0.1	0.001	0.001
34	URML	2	0.2	0.002	0.002
35	URMM	2	0.2	0.002	0.002
36	MH	1	0.1	0.001	0.001
B1	Major Bridge	N/A	N/A	N/A	N/A
B2	Continuous Bridge	N/A	N/A	N/A	N/A
B3	S.S. Bridge	N/A	N/A	N/A	N/A

Table 13.6: Indoor Casualty Rates by Model Building Type for Complete Structural Damage (No Collapse)

#	Building Type	Casualty Severity Level			
		Severity 1 (%)	Severity 2 (%)	Severity 3 (%)	Severity 4 (%)
1	W1	5	1	0.01	0.01
2	W2	5	1	0.01	0.01
3	S1L	5	1	0.01	0.01
4	S1M	5	1	0.01	0.01
5	S1H	5	1	0.01	0.01
6	S2L	5	1	0.01	0.01
7	S2M	5	1	0.01	0.01
8	S2H	5	1	0.01	0.01
9	S3	5	1	0.01	0.01
10	S4L	5	1	0.01	0.01
11	S4M	5	1	0.01	0.01
12	S4H	5	1	0.01	0.01
13	S5L	5	1	0.01	0.01
14	S5M	5	1	0.01	0.01
15	S5H	5	1	0.01	0.01
16	C1L	5	1	0.01	0.01
17	C1M	5	1	0.01	0.01
18	C1H	5	1	0.01	0.01
19	C2L	5	1	0.01	0.01
20	C2M	5	1	0.01	0.01
21	C2H	5	1	0.01	0.01
22	C3L	5	1	0.01	0.01
23	C3M	5	1	0.01	0.01
24	C3H	5	1	0.01	0.01
25	PC1	5	1	0.01	0.01
26	PC2L	5	1	0.01	0.01
27	PC2M	5	1	0.01	0.01
28	PC2H	5	1	0.01	0.01
29	RM1L	5	1	0.01	0.01
30	RM1M	5	1	0.01	0.01
31	RM2L	5	1	0.01	0.01
32	RM2M	5	1	0.01	0.01
33	RM2H	5	1	0.01	0.01
34	URML	10	2	0.02	0.02
35	URMM	10	2	0.02	0.02
36	MH	5	1	0.01	0.01
B1	Major Bridge	17	20	37	7
B2	Continuous Bridge	17	20	37	7
B3	S.S. Bridge	5	25	20	5

Table 13.7: Indoor Casualty Rates by Model Building Type for Complete Structural Damage (With Collapse)

#	Building Type	Casualty Severity Level			
		Severity 1 (%)	Severity 2 (%)	Severity 3 (%)	Severity 4 (%)
1	W1	40	20	3	5
2	W2	40	20	5	10
3	S1L	40	20	5	10
4	S1M	40	20	5	10
5	S1H	40	20	5	10
6	S2L	40	20	5	10
7	S2M	40	20	5	10
8	S2H	40	20	5	10
9	S3	40	20	3	5
10	S4L	40	20	5	10
11	S4M	40	20	5	10
12	S4H	40	20	5	10
13	S5L	40	20	5	10
14	S5M	40	20	5	10
15	S5H	40	20	5	10
16	C1L	40	20	5	10
17	C1M	40	20	5	10
18	C1H	40	20	5	10
19	C2L	40	20	5	10
20	C2M	40	20	5	10
21	C2H	40	20	5	10
22	C3L	40	20	5	10
23	C3M	40	20	5	10
24	C3H	40	20	5	10
25	PC1	40	20	5	10
26	PC2L	40	20	5	10
27	PC2M	40	20	5	10
28	PC2H	40	20	5	10
29	RM1L	40	20	5	10
30	RM1M	40	20	5	10
31	RM2L	40	20	5	10
32	RM2M	40	20	5	10
33	RM2H	40	20	5	10
34	URML	40	20	5	10
35	URMM	40	20	5	10
36	MH	40	20	3	5
B1	Major Bridge	N/A	N/A	N/A	N/A
B2	Continuous Bridge	N/A	N/A	N/A	N/A
B3	S.S. Bridge	N/A	N/A	N/A	N/A

Table 13.8: Collapse Rates by Model Building Type for Complete Structural Damage

	Model Building Type	Probability of Collapse Given a Complete Damage State*
1	W1	3.0%
2	W2	3.0%
3	S1L	8.0%
4	S1M	5.0%
5	S1H	3.0%
6	S2L	8.0%
7	S2M	5.0%
8	S2H	3.0%
9	S3	3.0%
10	S4L	8.0%
11	S4M	5.0%
12	S4H	3.0%
13	S5L	8.0%
14	S5M	5.0%
15	S5H	3.0%
16	C1L	13.0%
17	C1M	10.0%
18	C1H	5.0%
19	C2L	13.0%
20	C2M	10.0%
21	C2H	5.0%
22	C3L	15.0%
23	C3M	13.0%
24	C3H	10.0%
25	PC1	15.0%
26	PC2L	15.0%
27	PC2M	13.0%
28	PC2H	10.0%
29	RM1L	13.0%
30	RM1M	10.0%
31	RM2L	13.0%
32	RM2M	10.0%
33	RM2H	5.0%
34	URML	15.0%
35	URMM	15.0%
36	MH	3.0%

* See Chapter 5, Section 5.3 for derivation of these values

* See Chapter 5 for derivation of these values

Table 13.9: Outdoor Casualty Rates by Model Building Type for Moderate Structural Damage*

#	Building Type	Casualty Severity Level			
		Severity 1 (%)	Severity 2 (%)	Severity 3 (%)	Severity 4 (%)
1	W1	0.05	0.005	0.0001	0.0001
2	W2	0.05	0.005	0	0
3	S1L	0.05	0.005	0	0
4	S1M	0.05	0.005	0	0
5	S1H	0.05	0.005	0	0
6	S2L	0.05	0.005	0	0
7	S2M	0.05	0.005	0	0
8	S2H	0.05	0.005	0	0
9	S3	0	0	0	0
10	S4L	0.05	0.005	0	0
11	S4M	0.05	0.005	0	0
12	S4H	0.05	0.005	0	0
13	S5L	0.05	0.005	0	0
14	S5M	0.05	0.005	0	0
15	S5H	0.05	0.005	0	0
16	C1L	0.05	0.005	0	0
17	C1M	0.05	0.005	0	0
18	C1H	0.05	0.005	0	0
19	C2L	0.05	0.005	0	0
20	C2M	0.05	0.005	0	0
21	C2H	0.05	0.005	0	0
22	C3L	0.05	0.005	0	0
23	C3M	0.05	0.005	0	0
24	C3H	0.05	0.005	0	0
25	PC1	0.05	0.005	0	0
26	PC2L	0.05	0.005	0	0
27	PC2M	0.05	0.005	0	0
28	PC2H	0.05	0.005	0	0
29	RM1L	0.05	0.005	0	0
30	RM1M	0.05	0.005	0	0
31	RM2L	0.05	0.005	0	0
32	RM2M	0.05	0.005	0	0
33	RM2H	0.05	0.005	0	0
34	URML	0.15	0.015	0.0003	0.0003
35	URMM	0.15	0.015	0.0003	0.0003
36	MH	0	0	0	0

* The model assumes that there are no outdoor casualties for slight structural damage.

Table 13.10: Outdoor Casualty Rates by Model Building Type for Extensive Structural Damage

#	Building Type	Casualty Severity Level			
		Severity 1 (%)	Severity 2 (%)	Severity 3 (%)	Severity 4 (%)
1	W1	0.3	0.03	0.0003	0.0003
2	W2	0.3	0.03	0.0003	0.0003
3	S1L	0.1	0.01	0.0001	0.0001
4	S1M	0.2	0.02	0.0002	0.0002
5	S1H	0.3	0.03	0.0003	0.0003
6	S2L	0.1	0.01	0.0001	0.0001
7	S2M	0.2	0.02	0.0002	0.0002
8	S2H	0.3	0.03	0.0003	0.0003
9	S3	0	0	0	0
10	S4L	0.1	0.01	0.0001	0.0001
11	S4M	0.2	0.02	0.0002	0.0002
12	S4H	0.3	0.03	0.0003	0.0003
13	S5L	0.2	0.02	0.0002	0.0002
14	S5M	0.4	0.04	0.0004	0.0004
15	S5H	0.6	0.06	0.0006	0.0006
16	C1L	0.1	0.01	0.0001	0.0001
17	C1M	0.2	0.02	0.0002	0.0002
18	C1H	0.3	0.03	0.0003	0.0003
19	C2L	0.1	0.01	0.0001	0.0001
20	C2M	0.2	0.02	0.0002	0.0002
21	C2H	0.3	0.03	0.0003	0.0003
22	C3L	0.2	0.02	0.0002	0.0002
23	C3M	0.4	0.04	0.0004	0.0004
24	C3H	0.6	0.06	0.0006	0.0006
25	PC1	0.2	0.02	0.0002	0.0002
26	PC2L	0.1	0.01	0.0001	0.0001
27	PC2M	0.2	0.02	0.0002	0.0002
28	PC2H	0.3	0.03	0.0003	0.0003
29	RM1L	0.2	0.02	0.0002	0.0002
30	RM1M	0.3	0.03	0.0003	0.0003
31	RM2L	0.2	0.02	0.0002	0.0002
32	RM2M	0.3	0.03	0.0003	0.0003
33	RM2H	0.4	0.04	0.0004	0.0004
34	URML	0.6	0.06	0.0006	0.0006
35	URMM	0.6	0.06	0.0006	0.0006
36	MH	0	0	0	0

Table 13.11: Outdoor Casualty Rates by Model Building Type for Complete Structural Damage

#	Building Type	Casualty Severity Level			
		Severity 1 (%)	Severity 2 (%)	Severity 3 (%)	Severity 4 (%)
1	W1	2	0.5	0.1	0.05
2	W2	2	0.5	0.1	0.05
3	S1L	2	0.5	0.1	0.1
4	S1M	2.2	0.7	0.2	0.2
5	S1H	2.5	1	0.3	0.3
6	S2L	2	0.5	0.1	0.1
7	S2M	2.2	0.7	0.2	0.2
8	S2H	2.5	1	0.3	0.3
9	S3	0.01	0.001	0.001	0.01
10	S4L	2	0.5	0.1	0.1
11	S4M	2.2	0.7	0.2	0.2
12	S4H	2.5	1	0.3	0.3
13	S5L	2.7	1	0.2	0.3
14	S5M	3	1.2	0.3	0.4
15	S5H	3.3	1.4	0.4	0.6
16	C1L	2	0.5	0.1	0.1
17	C1M	2.2	0.7	0.2	0.2
18	C1H	2.5	1	0.3	0.3
19	C2L	2	0.5	0.1	0.1
20	C2M	2.2	0.7	0.2	0.2
21	C2H	2.5	1	0.3	0.3
22	C3L	2.7	1	0.2	0.3
23	C3M	3	1.2	0.3	0.4
24	C3H	3.3	1.4	0.4	0.6
25	PC1	2	0.5	0.1	0.1
26	PC2L	2.7	1	0.2	0.3
27	PC2M	3	1.2	0.3	0.4
28	PC2H	3.3	1.4	0.4	0.6
29	RM1L	2	0.5	0.1	0.1
30	RM1M	2.2	0.7	0.2	0.2
31	RM2L	2	0.5	0.1	0.1
32	RM2M	2.2	0.7	0.2	0.2
33	RM2H	2.5	1	0.3	0.3
34	URML	5	2	0.4	0.6
35	URMM	5	2	0.4	0.6
36	MH	0.01	0.001	0.001	0.01

13.2 Description of Methodology

The casualty model is complementary to the concepts put forward by some other models (Coburn and Spence, 1992; Murkami, 1992, Shiono, et. al., 1991). The Coburn and Spence model uses the same four-level injury severity scale (light injuries, hospitalized injuries, life threatening injuries and deaths) and underlying concepts associated with building collapse. However, it is not in event tree format and does not account for non-collapse (damage) related casualties, nor does it account for the population not indoors at the time of earthquake. The Murkami model is an event tree model that includes only fatalities caused by collapsed buildings and does not account for lesser injuries. Shiono's model is similar to the other two models and only estimated fatalities.

The methodology takes into account a wider range of causal relationships in the casualty modeling. It is an extension of the model proposed by Stojanovski and Dong (1994).

13.2.1 Earthquake Casualty Model

Casualties caused by a postulated earthquake can be modeled by developing a tree of events leading to their occurrence. As with any event tree, the earthquake-related casualty event tree begins with an initiating event (earthquake scenario) and follows the possible course of events leading to loss of life or injuries. The logic of its construction is forward (inductive). At each node of the tree, the (node branching) question is: What happens if the preceding event leading to the node occurs? The answers to this question are represented by the branches of the tree. The number of branches from any node is equal to the number of answers defined for the node branching question. Each branch of the tree is assigned a probability of occurrence. As noted earlier, data for earthquake related casualties are relatively scarce, particularly for U.S. earthquakes. Therefore, to some extent the casualty rates are inferred from the available data statistics and combined with expert opinion.

As an example, one particular severity of casualty, the expected number of occupants killed in a building during a given earthquake, could be simulated with an event tree as shown in Figure 13.1. For illustrative purposes it contains only "occupants killed," as events of interest and does not depict lesser severities of casualties. Evaluation of the branching probabilities constitutes the main effort in the earthquake casualty modeling. Assuming that all the branching probabilities are known or inferred, the probability of an occupant being killed (P_{killed}) is given as follows.

(Various events are described in Figure 13.1)

$$P_{killed} = P_A * P_E + P_B * P_F + P_C * P_G + P_D * (P_H * P_J + P_I * P_K) \qquad (13\text{-}2)$$

By introducing the substitutions

$$P_{killed \mid collapse} = P_D * P_I * P_K \qquad (13\text{-}3)$$

and

$$P_{killed\,|\,no\text{-}collapse} = P_A*P_E + P_B*P_F + P_C*P_G + P_D*P_H*P_J \qquad (13\text{-}4)$$

Equation (13-2) could be simply re-written as:

$$P_{killed} = P_{killed\,|\,collapse} + P_{killed\,|\,no\text{-}collapse} \qquad (13\text{-}5)$$

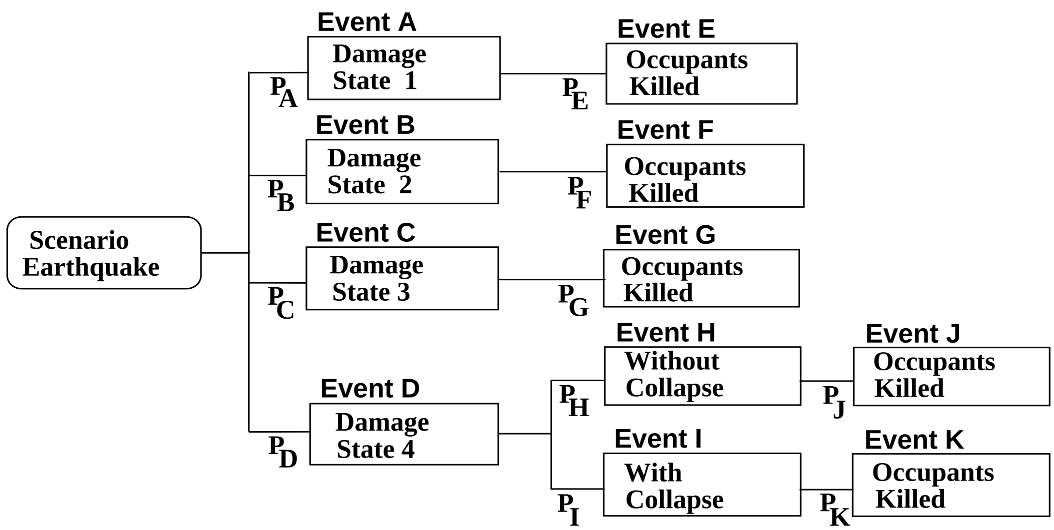


Figure 13.1 Casualty Event Tree Modeling.

The first term in equation 13-5 represents casualties associated with the building collapse. The second term represents casualties associated with the level of non-collapse damage the building sustains during the earthquake. Records from past earthquakes show that for different regions in the world with different kinds of construction there are different threshold intensities at which the first term begins to dominate. For intensities below that shaking level, casualties are primarily damage or non-collapse related. For intensities above that level, the collapse, often of only a few structures, may control the casualty pattern.

The expected number of occupants killed ($EN_{occupants\ killed}$) is a product of the number of occupants of the building at the time of earthquake ($N_{occupants}$) and the probability of an occupant being killed (P_{killed}).

$$EN_{occupants\ killed} = N_{occupants}*P_{killed} \qquad (13\text{-}6)$$

Figure 13.2 presents a more complete earthquake related casualty event tree for indoor casualties, which is used in the methodology. The branching probabilities are not shown in the figure in order to make the model presentation simpler. The events are represented with rectangular boxes, with a short event or state description given in each box. The symbol "<" attached to an event box means that branching out from that node is identical to branching from other nodes for the same category event (obviously, the appropriate probabilities would be different).

The event tree in Figure 13.2 is conceptual. It integrates several different event trees into one (light injuries, injuries requiring medical care, life threatening injuries and deaths) for different occupancy types (residential, commercial, industrial, commuting) for people inside buildings. A similar event tree for outdoor casualties is used in the model. Casualty rates are different depending on the preceding causal events: model building type, damage state, collapse, etc.

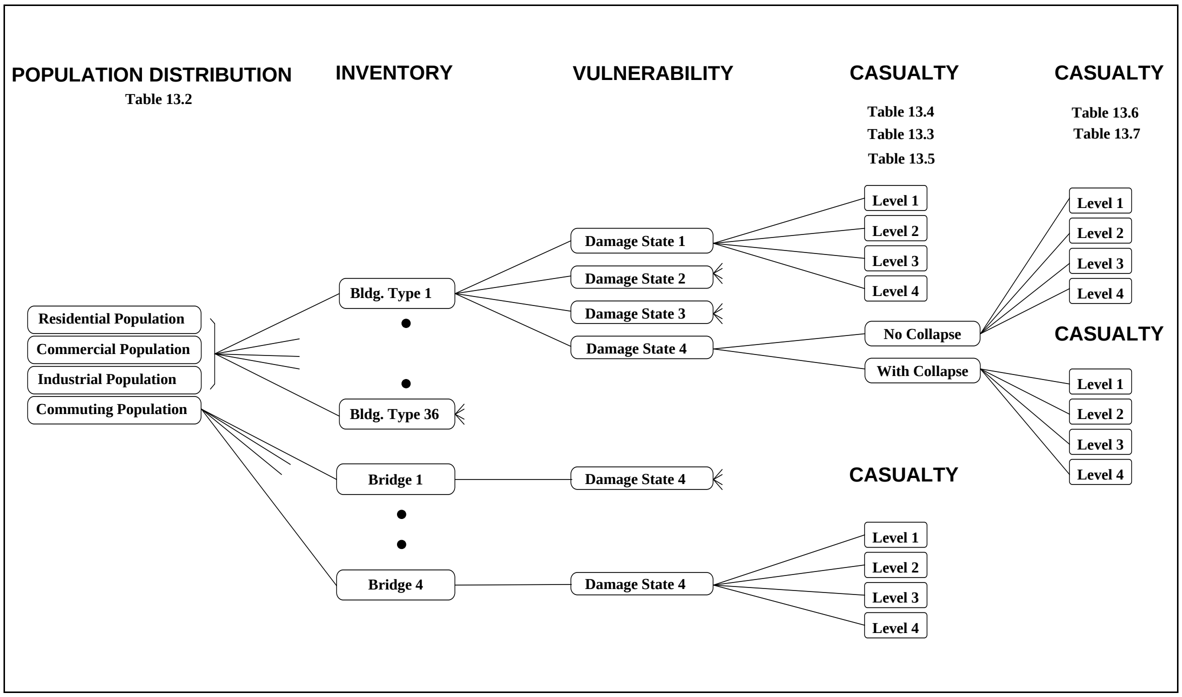


Figure 13.2: Indoor Casualty Event Tree Model.

13.2.2 Alternative Estimation of Casualty Rates

In the absence of adequate U.S.-specific casualty data (as a consequence of structural collapse), international data on the casualty rates for specific structural types may be used. If overseas casualty rates are used, U.S. construction practices, design and construction quality would have to be reflected in the appropriate region-specific fragility curves. If average worldwide casualty statistics or data from one or a few other countries are to be used for collapse-related casualty modeling in the United States, special attention must be given to the relationship between the U.S. structural types and the structural types represented by these other data sets. Also, appropriate mapping between injury classification scales must be established. Finally, it is possible that differing levels of earthquake preparedness, such as the effectiveness of the emergency medical system, and the training of the public in personal protective measures, such as "duck and cover,” might cause U.S. casualty rates to differ from those overseas, but this is unlikely to be a significant factor in cases of collapse, and at the present no data is available on these kinds of issues.

Published data on collapse-related casualty rates is limited. Noji (1990) provided this type of data for stone masonry and precast concrete buildings based on data from the 1988 Armenia earthquake. Murakami (1992) used these rates in a model that simulated the fatalities from the same event. Durkin and Murakami (1989) reported casualty rates for two reinforced concrete buildings collapsed during the 1985 Mexico and 1986 San Salvador earthquakes. Shiono et al. (1991) provided fatality rates after collapse for most common worldwide structural types. Coburn et al. (1992) have summarized approximate casualty rates for masonry and reinforced concrete structures based on worldwide data.

The casualty patterns for people who evacuate collapsed buildings, either before or immediately after the collapse, are more difficult to quantify. Statistical data on these casualty patterns is lacking, since in most post-earthquake reconnaissance efforts these injuries are not distinguished from other causes of injuries. In some cases, the lighter injuries may not be reported. An assumption may be applied that those who manage to evacuate are neither killed nor receive life threatening injuries. Often it is assumed that 50% of the occupants of the first floor manage to evacuate.

13.2.3 Casualties Due to Outdoor Falling Hazards

Experience in earthquakes overseas and in the United States has shown that a number of casualties occur outside buildings due to falling materials. People that are outside, but close to buildings could be hurt by structural or non-structural elements falling from the buildings. Examples are damaged parapets, loosened bricks, broken window glass, signage, awnings, or non-structural panels. In the 1987 Whittier Narrows earthquake a student at California State University, Los Angeles was killed when a concrete panel fell from a parking structure, and in the 1983 Coalinga earthquake one person was severely injured when the façade of a building collapsed onto the sidewalk and two people sitting in a parked car were hit by bricks from a collapsing building. Five people in San Francisco died when a brick wall collapsed onto their cars during the Loma Prieta earthquake. In the United States, casualties due to outdoor falling hazards have been caused primarily by falling unreinforced masonry, which may cause damage to an adjoining building and result in casualties, or fall directly on people outside the building.

People outside of buildings are less likely to be injured or killed than those inside buildings. For example, in the Loma Prieta earthquake out of 185 people who were injured or killed in Santa Cruz County, 20 people were outside and 1 was in a car (Wagner, 1996). An epidemiological study of casualties in the Loma Prieta earthquake indicates that injury risk in Santa Cruz County was 2.87 times higher for those in a building versus outside of a building (Jones et al., 1994). Note that the sample of residents surveyed was located mostly in suburban and rural surroundings. It is quite possible for a given earthquake to occur at a time of day and in a densely built-up locale where relatively more exterior casualties would occur. The Hazus methodology is based on probable outcomes, not the "worst case scenario."

This model attempts to account for casualties due to falling hazards, particularly with respect to areas where people congregate such as sidewalks. To accomplish this, the number of people on sidewalks or similar exterior areas is estimated from Table 13.2. The table is designed to prevent double counting of casualties from outdoor falling hazards with building occupant casualties.

The model for estimating casualties due to outside fall hazards is an event tree similar to that for indoor casualties. One difference is that the outdoor casualty event tree does not branch into collapse or no collapse for the complete damage state. Instead, the four severities of casualties depend only on the damage state of the building. The justification for this simplification is that people outside of buildings are much less likely to be trapped by collapsed floors. Another difference is that the model assumes that slight structural damage does not generate outdoor casualties. This is equivalent to eliminating Damage State 1 from the event tree in Figure 13.2. The probabilities for the event tree branches are in Tables 13.9 through 13.11.

13.2.4 Casualty Rates Resulting from Bridge Collapse

The model attempts to estimate casualties to people either on or under bridges that experience complete damage. The number of people on or under bridges is calculated from Table 13.2 and equation 13-1. The bridge casualty rates are found in Table 13.6.

Single Span Bridges

One reference that reports on many aspects of a single span bridge collapse is "Loma Prieta Earthquake October 17, 1989; I-80 San Francisco - Oakland Bay Bridge, Closure Span Collapse," published by the California Highway Patrol (Golden Gate MAIT, 1990). This document systematically reports most of the facts related to the collapse of one of the spans of the bridge. The only fatality was recorded approximately half an hour after the event, when a car drove into the gap created by the collapse.

Estimates of casualty rates for single span (SS) bridges are provided in Table 13.6 (Casualty Rates for Complete Structural damage) only. Lack of data did not allow similar inferences for other damage states.

Major and Continuous Bridges

A report published by the California Highway Patrol "Loma Prieta Earthquake October 17, 1989; I-880 Cypress Street Viaduct Structure Collapse," (Golden Gate MAIT, 1990) summarizes many aspects of a continuous (major) bridge collapse. This reference systematically reports most of the facts related to the collapse of the structure. Most of the injuries and fatalities occurred on the lower northbound deck as a consequence of the collapse of the upper deck onto the lower deck. A significant portion of injuries and fatalities also occurred among the people driving on the upper southbound deck. A small portion of casualties resulted from vehicles on the surface streets adjacent to the collapsed structure.

For casualty rates for major and continuous bridges, casualty statistics on the upper deck of the Cypress Viaduct and on the adjacent surface streets have been used. Double decker highway bridges are unusual and are not specifically modeled in Hazus. Thus casualty statistics associated with the vehicles on the lower deck are not considered representative.

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Chapter 14
Direct Social Losses - Displaced Households Due to Loss of Housing Habitability and Short Term Shelter Needs

14.1 Introduction

Earthquakes can cause loss of function or habitability of buildings that contain housing units, resulting in approximately predictable numbers of displaced households. These households may need alternative short-term shelter, provided by family, friends, renting apartments or houses, or public shelters provided by relief organizations such as the Red Cross, Salvation Army, and others. For units where repair takes longer than a few weeks, long-term alternative housing can be accommodated by importing mobile homes, occupancy of vacant units, net emigration from the impacted area, and, eventually, by the repair or reconstruction of new public and private housing. While the number of people seeking short-term public shelter is of great concern to emergency response organizations, the longer-term impacts on the housing stock are of great concern to local governments, such as cities and counties. The methodology highlighting the Shelter component is shown in Flowchart 14.1.

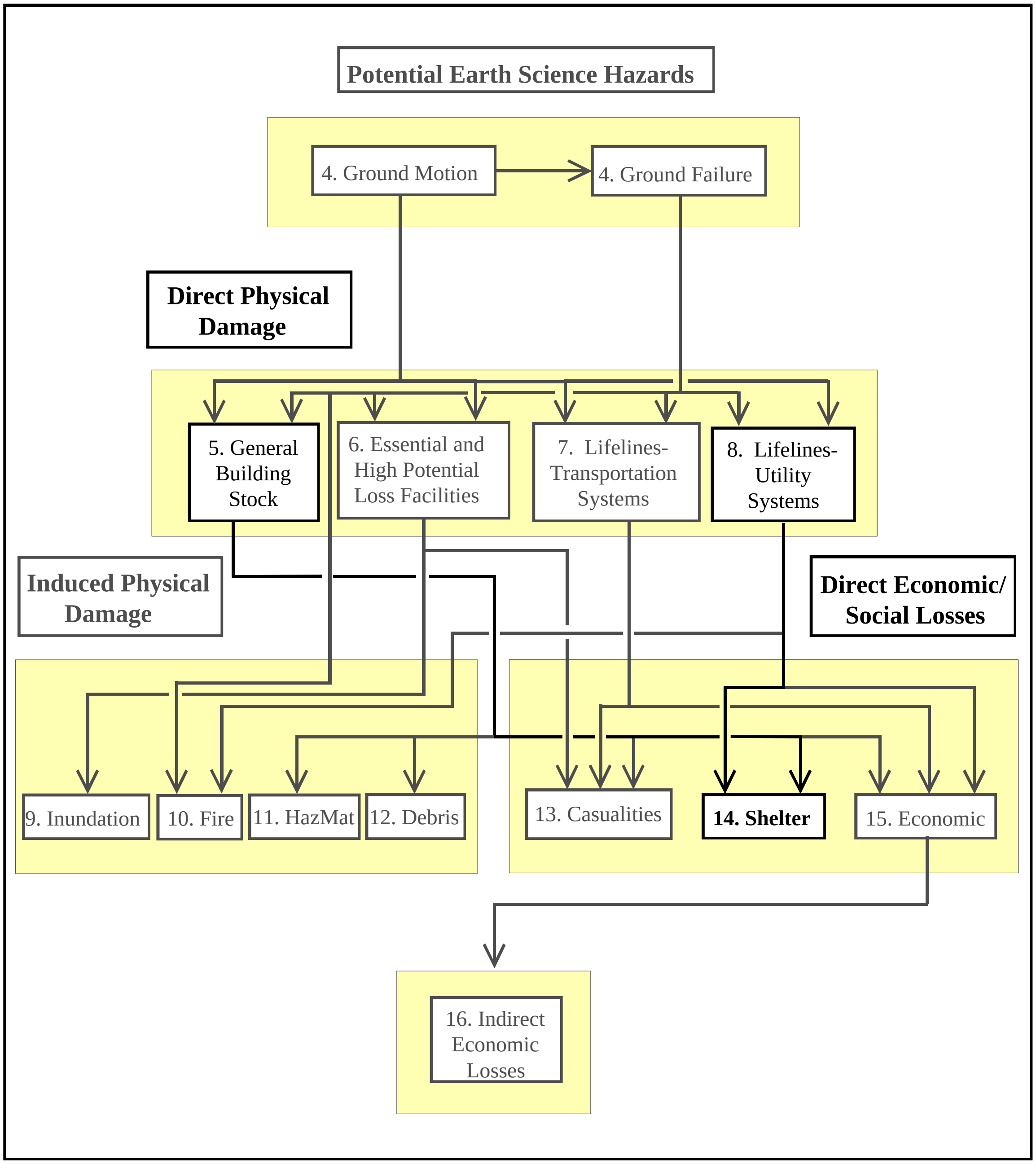
14.1.1 Scope

The shelter model provides two estimates:

- The number of displaced households (due to loss of habitability)
- The number of people requiring only short-term shelter

Loss of habitability is calculated directly from damage to the residential occupancy inventory, and from loss of water and power. The methodology for calculating short-term shelter requirements recognizes that only a portion of those displaced from their homes will seek public shelter, and some will seek shelter even though their residence may have no or insignificant damage.

Households may also be displaced as result of fire following earthquake, inundation (or the threat of inundation) due to dam failure, and by significant hazardous waste releases. This module does not specifically deal with these issues, but an approximate estimate of displacement due to fire or inundation can be obtained by multiplying the residential inventory in affected census tracts by the areas of fire damage or inundation derived from those modules. The hazardous materials module is confined to identifying locations of hazardous materials and no methodology for calculations of damage or loss is provided. If the particular characteristics of the study region give the user cause for concern about the possibility of housing loss from fire, dam failure, or hazardous materials, it would be advisable to initiate specific studies directed towards the problem, as a Level 3 study.



Flowchart 14.1: Direct Social Losses (Displaced Households) Relationship to other Components of the Earthquake Loss Estimation Methodology

14.2 Displaced Households - Form of Loss Estimate

The total number of uninhabitable dwelling units (#UNU) for each census tract of the study region is the output of this portion of the model. In addition, by applying an occupancy rate (households vs. dwelling units), the model converts the habitability data to the number of displaced households. The number of displaced households will be used in Section 14.3 to estimate the short-term shelter needs.

14.2.1 Input Requirements - Displaced Households

The following inputs are required to compute the number of uninhabitable dwelling units and the number of displaced households. The total number of units or households is provided in the default inventory based on census data (Section 3.6.2 of Chapter 3). The user can modify any values based on improved information.

- Total Number of Single-Family Dwelling Units (**#SFU)**
- Total Number of Multi-Family Dwelling Units (**#MFU**)
- Total Number of Households (**#HH**)
- Damage state probability for moderate structural damage in the single-family residential occupancy class (**%SFM**).
- Damage state probability for extensive structural damage state in the single-family residential occupancy class (**%SFE**).
- Damage state probability for complete structural damage state in the single-family residential occupancy class (**%SFC**).
- Damage state probability for moderate structural damage state in the multi- family residential occupancy class (**%MFM**).
- Damage state probability for extensive structural damage state in the multi- family residential occupancy class (**%MFE**).
- Damage state probability for complete structural damage state in the multi- family residential occupancy class (**%MFC**).

  [Note: The probabilities %SFM, %SFE, %SFC, %MFM, %MFE, and %MFC are provided by the Direct Physical Damage Module - Buildings (Chapter 5)].

14.2.2 Description of Methodology

The estimated number of uninhabitable dwelling units is calculated by combining a) the number of uninhabitable dwelling units due to actual structural damage, and b) the number of damaged units that are perceived to be uninhabitable by their occupants. Based on comparisons with previous work (Perkins, 1992; Perkins and Harrald, et. al., unpublished), the methodology considers all dwelling units located in buildings that are in the complete damage state to be uninhabitable. In addition, dwelling units that are in moderately and extensively damaged multi-family structures are also considered to be uninhabitable due to the fact that renters perceive some moderately damaged rental property as uninhabitable. On the other hand, those living in single-family homes are much more likely to tolerate damage and continue to live in their home. By applying an occupancy rate (households vs. dwelling units), the total number of displaced households (#DH) is calculated by the following relationship.

$$\%SF = w_{SFM} \times \%SFM + w_{SFE} \times \%SFE + w_{SFC} \times \%SFC$$
$$\%MF = w_{MFM} \times \%MFM + w_{MFE} \times \%MFE + w_{MFC} \times \%MFC$$
$$\#DH = (\#SFU \times \%SF + \#MFU \times \%MF) * \left(\frac{\#HH}{\#SFU + \#MFU} \right) \tag{14-1}$$

The values in Table 14.1 are provided as defaults. Due to the subjective nature of perceptions, users may want to change these values[1].

Table 14.1: Default Values for Damage State Probabilities

Weight Factor	Default Value
w_{SFM}	0.0
w_{SFE}	0.0
w_{SFC}	1.0
w_{MFM}	0.0
w_{MFE}	0.9
w_{MFC}	1.0

14.3 Short Term Shelter Needs - Form of Loss Estimate

All households living in uninhabitable dwellings will seek alternative shelter. Many will stay with friends and relatives or in the family car. Some will stay in public shelters provided by the Red Cross or others, or rent motel or apartment lodging. This methodology estimates the number of displaced persons seeking public shelter. In addition, observations from past disasters show that approximately 80% of the pre-disaster homeless will seek public shelter. Finally, data from Northridge indicates that approximately one-third of those in public shelters came from residences with little or no structural damage. Depending on the degree to which infrastructure damage is incorporated into #DH, that number of displaced persons could be increased by up to 50% to account for "perceived" structural damage as well as lack of water and power.

14.3.1 Input Requirements - Short-Term Shelter Needs

The inputs required to estimate short-term housing needs are obtained from the displaced household calculations in Section 14.2 and from the default census data. As with the entire

[1]For guidance, research has shown a much clearer relationship between the red-, yellow- and green- tagging assigned by building inspectors and perceived habitability than between damage state and perceived habitability (Perkins and Harrald, et al., unpublished). Red- and yellow-tagged multi-family dwellings are considered uninhabitable, while only red-tagged single family homes are considered uninhabitable.

methodology, the census data can be modified with improved user information. The inputs listed below are the required census data inputs.

- Number of people in census tract (POP)
- Number of Households (#HH)
- Percentage of households whose income is under $10,000 ($HI_1$)
- Percentage of households whose income is $10,001 to $15,000 ($HI_2$)
- Percentage of households whose income is $15,001 to $25,000 ($HI_3$)
- Percentage of households whose income is $25,001 to $35,000 ($HI_4$)
- Percentage of households whose income is over $35,000 ($HI_5$)
- Percentage of white households (HE_1)
- Percentage of black households (HE_2)
- Percentage of Hispanic households (HE_3)
- Percentage of Native American households (HE_4)
- Percentage of Asian households (HE_5)
- Percentage of households owned by householder (HO_1)
- Percentage of households rented by householder (HO_2)
- Percentage of population under 16 years old (HA_1)
- Percentage of population between 16 and 65 years old (HA_2)
- Percentage of population over 65 years old (HA_3)

14.3.2 Description of Methodology

Those seeking public shelter can be estimated from experience in past disasters, including both hurricanes and earthquakes. Those seeking shelter typically have very low incomes, for these families have fewer options. In addition, they tend to have young children or are over 65. Finally, even given similar incomes, Hispanic populations from Central America and Mexico tend to be more concerned about reoccupying buildings than other groups. This tendency appears to be because of the fear of collapsed buildings instilled from past disastrous Latin American earthquakes.

The number of people who require short-term housing can be calculated using the following relationship.

$$\#STP = \sum_{i=1}^{5}\sum_{j=1}^{5}\sum_{k=1}^{2}\sum_{l=1}^{3}\left(\alpha_{ijkl} * \left(\frac{\#DH * POP}{\#HH}\right) * HI_i * HE_j * HO_k * HA_l\right) \qquad (14\text{-}2)$$

where

#STP	- Number of people requiring short term housing
α_{ijkl}	- is a constant defined by Equation 14-5
HI_i	- Percentage of population in the i^{th} income class

HE_j - Percentage of population in the j^{th} ethnic class
HO_k - Percentage of population in the k^{th} ownership class
HA_l - Percentage of population in the l^{th} age class
POP - Population in census tract

The value of the α_{ijkl} constant can be calculated using a combination of shelter category "weights" (Table 14.2) (which sum to 1.00) and assigning a relative modification factor (Table 14.3) for each subdivision of each category. In the methodology, default values for the variables for ownership and age are zero.

$$\alpha_{ijkl} = (IW * IM_i) + (EW * EM_j) + (OW * OM_k) + (AW * AM_l) \quad (14\text{-}3)$$

Table 14.2: Shelter Category Weights

Class	Description	Default
IW	Income Weighting Factor	0.73
EW	Ethnic Weighting Factor	0.27
OW	Ownership Weighting Factor	0.00
AW	Age Weighting Factor	0.00

Table 14.3: Shelter Relative Modification Factors

Class	Description	Default
Income		
IM_1	Household Income < $10000	0.62
IM_2	$10000 < Household Income < $15000	0.42
IM_3	$15000 < Household Income < $25000	0.29
IM_4	$25000 < Household Income < $35000	0.22
IM_5	$35000 < Household Income	0.13
Ethnic		
EM_1	White	0.24
EM_2	Black	0.48
EM_3	Hispanic	0.47
EM_4	Asian	0.26
EM_5	Native American	0.26
Ownership		
OM_1	Own Dwelling Unit	0.40
OM_2	Rent Dwelling Unit	0.40
Age		
AM_1	Population Under 16 Years Old	0.40
AM_2	Population Between 16 and 65 Years Old	0.40
AM_3	Population Over 65 Years Old	0.40

Within each of these categories, the default relative modification factors given in Table 14.3 can be used to calculate α_{ijkl} values (i.e., estimate the percentage of each category that will seek shelter) (with an average value for each category being 0.33 to 0.45). These constants were originally developed by George Washington University under contract with the Red Cross and are based on "expert" opinion (Harrald, Fouladi, and Al-Hajj, 1992). Recently collected data from over 200 victims of the Northridge earthquake disaster were analyzed and used in finalizing these constants (Harrald, et. al., 1994). The modification factors provided in Table 14.3 are the mean of the George Washington University modification factors described in these two reports. Data for Native Americans are extremely scarce. Some information from Alaskan disasters indicates that the factor for those seeking shelter is similar for whites and Asians.

14.3.3 User-defined Changes to Weight and Modification Factors

In the methodology, weights can be added which account for age and ownership. As noted in Section 14.3.1, the required population distribution data are available. Remember that the weights must sum to 1.0. Young families tended to seek shelter in a larger proportion than other age groups in Northridge, in part because of lower per capita income. This result is consistent with data from hurricanes. In hurricanes, and Northridge, the elderly populations were also more likely to seek public shelter than average. Use special care if you want to add ownership to ensure that you are not double counting because the multi-family versus single-family issue has already been taken into account when estimating habitability (moderately damaged multi-family units are considered uninhabitable while moderately damaged single family units are considered habitable).

Most recent earthquake disasters and hurricanes have occurred in warm weather areas. A major non-shelter location was the family car and tents in the family's backyard. Should an earthquake occur in a colder climate, more people would probably find these alternate shelters unacceptable. In the methodology, the user is able to adjust the factors specifying the percentage of those displaced that seek public shelter (i.e. the shelter relative modification factors in Table 14.3). When making modifications for weather, be careful not to double count. The adjustment for this module should only take into account the larger percentage of those displaced that will seek public shelter (versus the family car or camping in one's backyard.)

14.3.4 Guidance for Estimates Using Advanced Data and Models

The recent Loma Prieta and Northridge earthquakes in California have not been catastrophic events. Although many people have been displaced in these recent earthquake disasters, the size of the area or the spottiness of the damage have left people with more than minimal incomes the options of alternate shelters.

As noted above, Hispanic populations from areas of Central America and Mexico tended to be more concerned about reoccupying buildings with insignificant or minor damage than other groups because of the fear of collapsed buildings instilled from past disastrous earthquakes in Latin America. Such tendencies will probably expand to all ethnic groups should a large number of casualties occur.

14.4 Guidance for Estimating Long-Term Housing Recovery

Although not calculated by the methodology, the damage to residential units (calculated in the general building stock module) can be combined with relationships between damage and restoration times (in the functional loss module) to estimate the need for longer-term replacement housing. Longer-term needs are accommodated by importing mobile homes, reductions in the vacancy rates, net emigration from an area, and eventual repair or reconstruction of the housing units. Because replacement of permanent housing is subject to normal market and financial forces, low-income housing is the last type of housing to be replaced.

Based on experience in Loma Prieta (Perkins, 1992) and preliminary Northridge analyses (Perkins and Harrald, et. al., unpublished) housing recovery times span a wide range, and are typically far longer than might be estimated from typical planning rules of thumb, and longer than most commercial, industrial and institutional recovery. Housing recovery tends to be very dependent on settlement of insurance claims, federal disaster relief, the effectiveness of the generally smaller contractors who do much residential work, and the financial viability of the home or apartment owner, together with actions taken by state and local governments to expedite the process, and public support of reconstruction (such as the potential desire for historic preservation). The median recovery time figures for residential occupancies shown in Table

15.11 reflect these issues, but there will tend to be very wide variation about the mean. In particular, recovery times for non-wood frame multi-family housing, especially low-income single room occupancy buildings, ought to be measured in years.

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Chapter 15
Direct Economic Losses

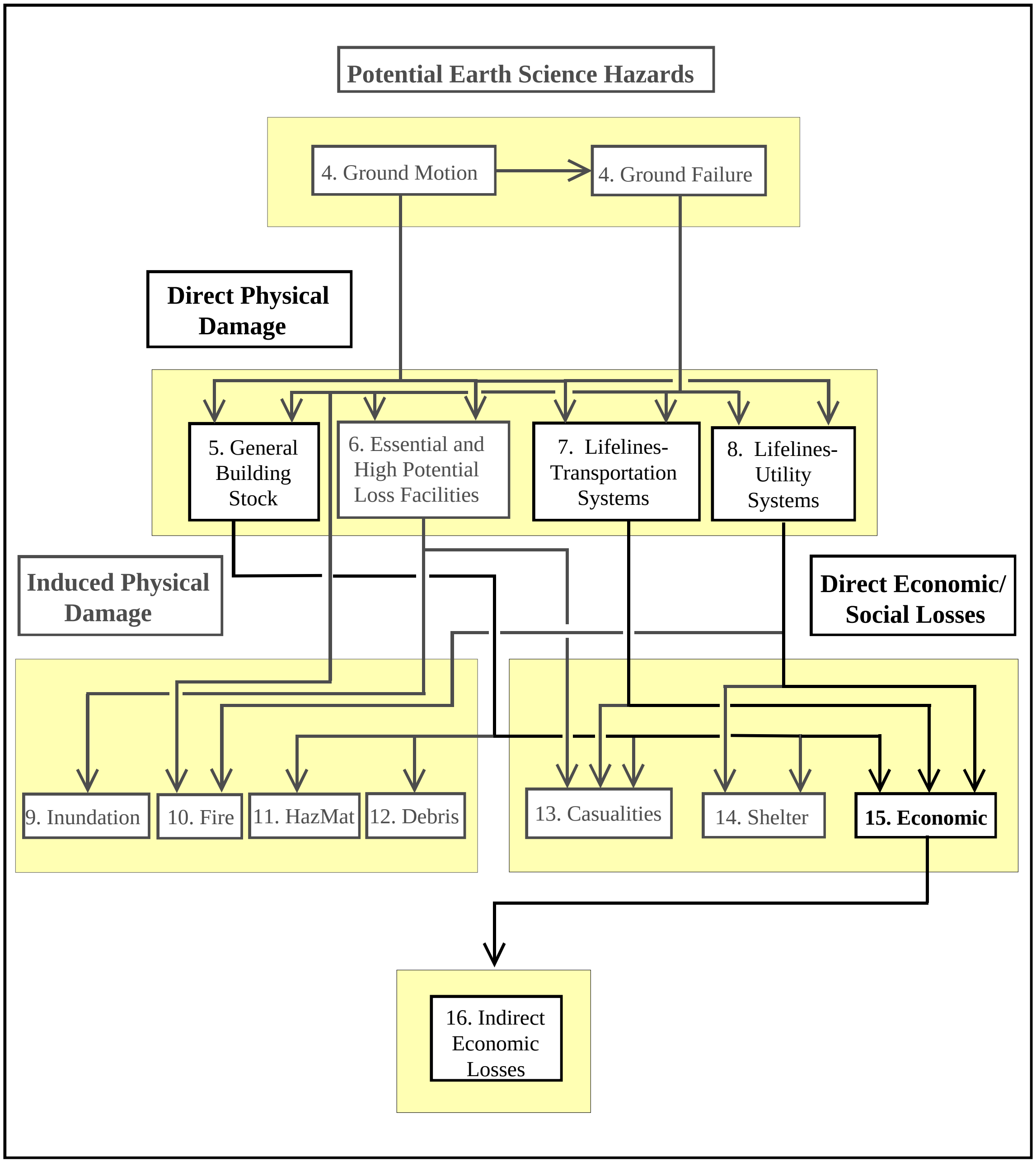
15.1 Introduction

This chapter describes the conversion of damage state information, developed in previous modules, into estimates of dollar loss. In the past, loss estimation studies have generally limited the consideration of loss to estimates of the repair and replacement costs of the building stock.

The methodology provides estimates of the structural and nonstructural repair costs caused by building damage and the associated loss of building contents and business inventory. Building damage can also cause additional losses by restricting the building's ability to function properly. To account for this, business interruption and rental income losses are estimated. These losses are calculated from the building damage estimates by use of methods described later. The methodology highlighting the Direct Economic Loss component is shown in Flowchart 15.1.

This expression of losses provides an estimate of the costs of building repair and replacement that is a frequently required output of a loss estimation study. The additional estimates of consequential losses give an indication of the immediate impact of such building damage on the community: the financial consequences to the community's businesses due to businesses interruption, the financial resources that will be needed to make good the damage, and an indication of job and housing losses.

In strict economic terms, buildings, inventories, and public facilities represent capital investments that produce income, and the value of the building and inventory will be the capitalized value of the income produced by the investment that created the building or inventory. Hence, if we estimate the dollar value of the buildings damaged or destroyed, and add the income lost from the absence of the functioning facilities we may be overestimating the indirect economic loss (Chapter 16). However, for the assessment of direct economic loss, the losses can be estimated and evaluated independently.



Flowchart 15.1: Direct Economic Losses Relationship to other Components of the Earthquake Loss Estimation Methodology

Since a significant use for loss estimation studies is expected to be that of providing input into future benefit-cost studies used to evaluate mitigation strategies and budgets, the list of these consequential losses is similar to that developed for the FEMA benefit-cost procedure described in FEMA publications 227 and 228, and 255 and 256. This procedure is, however, limited to conventional real-estate parameters similar to those used in evaluating the feasibility of a development project and does not attempt to evaluate the full range of socio/economic impacts that might follow specific mitigation strategies.

Thus, for this loss estimation methodology, even though the derivation of these consequential losses represents a considerable expansion of the normal consideration of building damage/loss, this module is still limited in its consideration of economic loss to those losses that can be directly derived from building and infrastructure damage, and that lend themselves to ready conversion from damage to dollars. The real socio/economic picture is much more complex: economic impacts may have major societal effects on individuals or discrete population groups, and there may be social impacts that ultimately manifest themselves in economic consequences. In many cases the linkages are hard to trace with accuracy and the effects, while easy to discern, are difficult to quantify because definite systematic data is lacking.

For example, the closing of the Oakland/San Francisco Bay Bridge for 30 days following the Loma Prieta earthquake of 1989 required approximately a quarter of a million daily users of the bridge to rearrange their travel patterns. Many individual commuters were forced to take a significantly longer and more costly route to their destinations. At the same time, other commuters changed to use of the BART rail system or bus services, which also altered their family expenditure patterns. More lengthy trips for business service travelers and material suppliers resulted in varying degrees of loss of productivity. Businesses directly related to normal operation of the bridge, such as gas stations and automobile repair shops on the approach routes to the bridge suffered losses.

Repairs to the bridge represented a direct cost to the state budget. At the same time, the revenues from bridge tolls were nonexistent. However, some businesses gained from closure: some gas stations had improved business, and revenues to other bridges, the BART system, and bus companies increased.

Increased commuting time resulted in loss of leisure and family time, and shifts in the customer and sales patterns of many small businesses resulted in an increase in normal business worries.

If this 30-day loss of function had, instead, been a period of years (as is the case for elements of the Bay Area Freeway system) the socio/economic impacts would have been profound and long lasting throughout the Bay region.

This example suggests the range of inter-related consequential impacts stemming from damage to a single structure: but these impacts were accompanied by a host of other impacts to individuals, businesses, institutions and communities that serve further to increase the complexity of post-earthquake effects. As understanding is gained of these interactions, and data collection becomes richer and more systematic, quantification of the consequential losses of earthquake damage can become broader and more accurate.

Given the complexity of the problem and the present paucity of data, the methodology focuses on a few key issues that are of critical importance to government and the community, that can be quantified with reasonable assurance, and that provide a picture of the cost consequences of building and infrastructure damage that are understandable and would be of major concern to a municipality or region. In addition, application of the methodology will provide information that would be useful in a more detailed study of a particular economic or social sector, such as impact on housing stock or on a significant local industry. Finally, the structure of the methodology should be of assistance in future data gathering efforts.

While the links between this module and the previous modules dealing with damage are very direct and the derivations are very transparent, the links between this module and that of Chapter 16, Indirect Economic Losses, are less so. While some of the estimates derived in this module, such as income loss by sector, building repair costs, and the loss of contents and inventories, may be imported directly into the Indirect Loss Module, some interpretation of the direct economic loss estimates would be necessary for a more detailed indirect economic loss study. It would be necessary, for example, to translate the repair and replacement times and costs derived in this module to monthly reconstruction investment estimates for use in a longer-term indirect loss estimate.

15.1.1 Scope

This chapter provides descriptions of the methodologies, the derivation of default data, and explanatory tables for a number of direct economic loss items, derived from estimates of building and lifeline damage. For building related items, methods for calculating the following dollar losses are provided:

- Building Repair and Replacement Costs
- Building Contents Losses
- Building Inventory Losses

To enable time dependent losses to be calculated, default values are provided for:

- Building Recovery Time and Loss of Function (business interruption) time

Procedures for calculating the following time dependent losses are provided:

- Relocation Expenses
- Loss of Proprietors' Income
- Rental Income Losses

For each lifeline, information is provided on replacement values and assumed numerical damage ratios corresponding to damage states. Chapters 7 and 8 provide restoration curves corresponding to lifeline damage states. With this information the cost of damage to lifelines and the elapsed time for their restoration could be calculated; however, no attempt is made to estimate losses due to interruption of customer service, alternative supply services, and the like.

The following lifelines are covered:

Transportation Systems
- Highway Systems
- Railroads
- Light Rail Systems
- Bus Systems
- Port Systems
- Ferry Services
- Airport Systems

Utility Systems:
- Potable Water
- Waste Water
- Oil
- Natural Gas
- Electric Power
- Communication

Dollar losses due to fire and inundation are not explicitly addressed. However, the methodology enables the area of inundation to be estimated and related to the quantity of building stock in the affected census tracts. This, in turn, can be converted into a dollar value.

In a similar manner, a value for building losses from fire can be estimated by relating the area of fire spread to the volume of construction and the construction cost. In both cases, the nature of damage states (which would vary from those of ground shaking damage) are not developed and estimates of dollar loss from these causes should be regarded as very broad estimates. In addition, since the concern is for earthquake-induced fire or inundation, the possibility of double counting of damage is present. More specific studies should be undertaken if the user believes that either fire or inundation might represent a serious risk.

Since the methodology goes no further than indicating sources of hazardous materials, no methodology is provided for estimating losses due to the release of such materials. Again, if the possibility of serious losses from this cause is a matter of concern, specific studies should be undertaken.

15.1.2 Form of Direct Economic Loss Estimates

Direct economic loss estimates are provided in 1994 dollars. In some instances, as in the cost of building replacement, a procedure is provided for the conversion of default dollar values to those prevalent at the time of the loss estimation study. In other instances, user provided information, such as local rental costs, would be provided in current dollar values.

15.1.3 Input Requirements

In general, input data for direct economic losses consists of building damage estimates from the direct physical damage module. The damage estimates are in the form of probabilities of being in each damage state, for each structural type or occupancy class. The building classification system is as discussed in Chapter 3. Damage states are discussed in detail in Chapter 5. Damage state probabilities are provided from the direct physical damage module for both structural and non-structural damage. These damage state probabilities are then converted to monetary losses using inventory information and economic data. For Default Data Analysis values, the buildings are classified into three broad occupancy/use-related categories: residential, commercial/institutional, and industrial. These categories are used to determine the non-structural element make-up of the buildings and the nature and value of their contents. For User-Supplied Data and Advanced Data and Models Analyses, a 28-category occupancy classification (See Table 15.1) is defined that provides for a more refined economic loss analysis. Building replacement cost data is provided for this classification level.

The types of economic data that the user will be expected to supply include repair and replacement costs, contents value for different occupancies, annual gross sales by occupancy, relocation expenses and income by occupancy. While default values are provided for these data, the user may wish to provide more accurate local values or update default values to current dollars.

Direct economic losses for transportation and lifeline systems are limited to the cost of repairing damage to the lifeline system. Default values are provided for replacement values of lifeline components as a guide. It is expected that in a User-Supplied Data Analysis, the user will input replacement values based on knowledge of lifeline values in the region.

Table 15.1: Building Occupancy Classes

No.	Label	Occupancy Class	Description
		Residential	
1	RES1	Single Family Dwelling	Detached House
2	RES2	Mobile Home	Mobile Home
3-8	RES3a-f	Multi Family Dwelling	Apartment/Condominium
9	RES4	Temporary Lodging	Hotel/Motel
10	RES5	Institutional Dormitory	Group Housing (military, college), Jails
11	RES6	Nursing Home	
		Commercial	
12	COM1	Retail Trade	Store
13	COM2	Wholesale Trade	Warehouse
14	COM3	Personal and Repair Services	Service Station/Shop
15	COM4	Professional/Technical Services	Offices
16	COM5	Banks/Financial Institutions	
17	COM6	Hospital	
18	COM7	Medical Office/Clinic	Offices
19	COM8	Entertainment & Recreation	Restaurants/Bars
20	COM9	Theaters	Theaters
21	COM10	Parking	Garages
		Industrial	
22	IND1	Heavy	Factory
23	IND2	Light	Factory
24	IND3	Food/Drugs/Chemicals	Factory
25	IND4	Metals/Minerals Processing	Factory
26	IND5	High Technology	Factory
27	IND6	Construction	Office
		Agriculture	
28	AGR1	Agriculture	
		Religion/Non-Profit	
29	REL1	Church	
		Government	
30	GOV1	General Services	Office
31	GOV2	Emergency Response	Police/Fire Station
		Education	
32	EDU1	Schools	
33	EDU2	Colleges/Universities	Does not include group housing

15.2 Description of Methodology: Buildings

This section describes the estimation of building-related direct economic losses.

15.2.1 Building Repair and Replacement Costs

To establish dollar loss estimates, the damage state probabilities must be converted to dollar loss equivalents. Losses will be due to both structural and non-structural damage. For a given occupancy and damage state, building repair and replacement costs are estimated as the product of the floor area of each building type within the given occupancy, the probability of the building type being in the given damage state, and repair costs of the building type per square foot for the given damage state, summed over all building types within the occupancy.

It can be argued that the true cost of buildings damaged or destroyed is their loss of market value, reflecting the age of the building, depreciation, and the like. Replacement value is a frequently requested output of a loss estimation study, because it gives an immediately understandable picture of the community building losses, and disaster assistance is currently granted on the basis of replacement value. In fact, market value is by no means constant in relation to replacement value. For example, typical estimates of market value include the value of the lot: in locations of high land cost, market value may greatly exceed replacement value (which excludes lot value). Moreover, building age does not necessarily result in a linear loss of market value: after a certain age some buildings begin to acquire additional value by virtue of architectural style and craftsmanship and true replacement cost might greatly exceed market value.

These issues may need to be considered in a detailed evaluation of the direct economic losses where particular building inventories or economic aspects of the damage are being evaluated. Full discussion of these and other related issues may be found in Howe and Cochrane, 1993.

For structural damage, losses are calculated as follows:

$$CS_{ds,i} = BRC_i * \sum_{i=1}^{33} PMBTSTR_{ds,i} * RCS_{ds,i} \tag{15-1}$$

$$CS_i = \sum_{ds=2}^{5} CS_{ds,i} \tag{15-2}$$

where:

$CS_{ds,i}$	cost of structural damage (repair and replacement costs) for damage state ds and occupancy i
BRC_j	building replacement cost of occupancy i as described in Chapter 3
$PMBTSTR_{ds,j}$	probability of occupancy i being in structural damage state ds, see Chapter 5
$RCS_{ds,i}$	structural repair and replacement ratio for occupancy i in damage state ds, Tables 15.2

The structural repair cost ratio for structural damage for each damage state and occupancyare shown in Table 15.2. Note that damage state "none" (ds = 1) does not contribute to the calculation of the cost of structural damage and thus the summation in Equation 15-2 is from ds = 2 to ds = 5.

A similar calculation is performed for non-structural damage. Non-structural damage is broken down into acceleration sensitive damage (damage to ceilings, equipment that is an integral part of the facility such as mechanical and electrical equipment, piping and elevators) and drift sensitive damage (partitions, exterior walls, ornamentation and glass). Non-structural damage does not include the damage to contents such as furniture and computers that is accounted for in Section 15.2.2. Non-structural damage costs are calculated as follows:

$$CNSA_{ds,i} = BRC_j * PONSA_{ds,i} * RCA_{ds,i}, \quad (15\text{-}3)$$

$$CNSA_i = \sum_{ds=2}^{5} CNSA_{ds,i} \quad (15\text{-}4)$$

$$CNSD_{ds,i} = BRC_i * PONSD_{ds,i} * RCD_{ds,i} \quad (15\text{-}5)$$

$$CNSD_i = \sum_{ds=2}^{5} CNSD_{ds,i} \quad (15\text{-}6)$$

where:

$CNSA_{ds,i}$	cost of acceleration-sensitive non-structural damage (repair and replacement costs) for damage state ds and occupancy i
$CNSA_i$	cost of acceleration-sensitive non-structural damage (repair and replacement costs) for occupancy i
$CNSD_{ds,i}$	cost of drift-sensitive non-structural damage (repair and replacement costs) for damage state ds and occupancy i
$CNSD_i$	cost of drift-sensitive non-structural damage (repair and replacement costs) for occupancy i
BRC_j	Building replacement cost of occupancy i as described in Chapter 3
$PONSA_{ds,i}$	probability of occupancy i being in non-structural acceleration sensitive damage state ds, see Chapter 5
$PONSD_{ds,i}$	probability of occupancy i being in non-structural drift sensitive damage state ds, see Chapter 5
$RCA_{ds,i}$	acceleration sensitive non-structural repair and replacement ratio for occupancy i in damage state ds (Table 15-3)
$RCD_{ds,i}$	drift sensitive non-structural repair and replacement ratio for occupancy i in damage state ds (Table 15-4)

The repair cost ratios for non-structural damage for each damage state are shown in Tables 15.3 and 15.4 for acceleration and drift sensitive non-structural components, respectively.

To determine the total cost of non-structural damage for occupancy class i (CNS_i), Equations 15-4 and 15-6 must be summed.

$$CNS_i = CNSA_i + CNSD_i \quad (15\text{-}7)$$

The total cost of building damage (CBD_i) for occupancy class i is the sum of the structural and non-structural damage.

$$CBD_i = CS_i + CNS_i \quad (15\text{-}8)$$

Finally, to determine the total cost of building damage (CBD), Equation 15-8 must be summed over all occupancy classes.

$$CBD = \sum_i CBD_i \quad (15\text{-}9)$$

15.2.1.1 Default Values for Building Repair Costs

Table 15.2 show the default values for the structural repair cost ratios related to the 33 occupancy classifications. The relative percentage of total building cost allocated to structural and non-structural components is derived from the *Means* component breakdowns for each occupancy class.

Tables 15.3 and 15.4 show the default values for the repair cost ratios of the acceleration sensitive and drift sensitive components. Acceleration sensitive non-structural components include hung ceilings, mechanical and electrical equipment, and elevators. Drift sensitive components include partitions, exterior wall panels, and glazing. The relative percentages of drift and acceleration sensitive components are based on the component breakdown provided in *Means.*

The damage ratios expressed as a percentage of the building replacement value. These values are consistent with and in the range of the damage definitions and corresponding damage ratios presented in *ATC-13 Earthquake Damage Evaluation Data for California*. For specific building inventories, at an Advanced Data and Models Analysis, more precise estimates of structural/non-structural quantity and cost relationships can be obtained by the user.

Table 15.2: Structural Repair Cost Ratios
(in % of building replacement cost)

No.	Label	Occupancy Class	Structural Damage State			
			Slight	Moderate	Extensive	Complete
		Residential				
1	RES1	Single Family Dwelling	0.5	2.3	11.7	23.4
2	RES2	Mobile Home	0.4	2.4	7.3	24.4
3-8	RES3a-f	Multi Family Dwelling	0.3	1.4	6.9	13.8
9	RES4	Temporary Lodging	0.2	1.4	6.8	13.6
10	RES5	Institutional Dormitory	0.4	1.9	9.4	18.8
11	RES6	Nursing Home	0.4	1.8	9.2	18.4
		Commercial				
12	COM1	Retail Trade	0.6	2.9	14.7	29.4
13	COM2	Wholesale Trade	0.6	3.2	16.2	32.4
14	COM3	Personal and Repair Services	0.3	1.6	8.1	16.2
15	COM4	Professional/Technical/ Business Services	0.4	1.9	9.6	19.2
16	COM5	Banks/Financial Institutions	0.3	1.4	6.9	13.8
17	COM6	Hospital	0.2	1.4	7.0	14.0
18	COM7	Medical Office/Clinic	0.3	1.4	7.2	14.4
19	COM8	Entertainment & Recreation	0.2	1.0	5.0	10.0
20	COM9	Theaters	0.3	1.2	6.1	12.2
21	COM10	Parking	1.3	6.1	30.4	60.9
		Industrial				
22	IND1	Heavy	0.4	1.6	7.8	15.7
23	IND2	Light	0.4	1.6	7.8	15.7
24	IND3	Food/Drugs/Chemicals	0.4	1.6	7.8	15.7
25	IND4	Metals/Minerals Processing	0.4	1.6	7.8	15.7
26	IND5	High Technology	0.4	1.6	7.8	15.7
27	IND6	Construction	0.4	1.6	7.8	15.7
		Agriculture				
28	AGR1	Agriculture	0.8	4.6	23.1	46.2
		Religion/Non-Profit				
29	REL1	Church/Membership Organization	0.3	2.0	9.9	19.8
		Government				
30	GOV1	General Services	0.3	1.8	9.0	17.9
31	GOV2	Emergency Response	0.3	1.5	7.7	15.3
		Education				
32	EDU1	Schools/Libraries	0.4	1.9	9.5	18.9
33	EDU2	Colleges/Universities	0.2	1.1	5.5	11.0

Table 15.3: Acceleration Sensitive Non-structural Repair Cost Ratios (in % of building replacement cost)

No.	Label	Occupancy Class	Acceleration Sensitive Non-structural Damage State			
			Slight	Moderate	Extensive	Complete
		Residential				
1	RES1	Single Family Dwelling	0.5	2.7	8.0	26.6
2	RES2	Mobile Home	0.8	3.8	11.3	37.8
3-8	RES3a-f	Multi Family Dwelling	0.8	4.3	13.1	43.7
9	RES4	Temporary Lodging	0.9	4.3	13.0	43.2
10	RES5	Institutional Dormitory	0.8	4.1	12.4	41.2
11	RES6	Nursing Home	0.8	4.1	12.2	40.8
		Commercial				
12	COM1	Retail Trade	0.8	4.4	12.9	43.1
13	COM2	Wholesale Trade	0.8	4.2	12.4	41.1
14	COM3	Personal and Repair Services	1.0	5	15	50.0
15	COM4	Professional/Technical/ Business Services	0.9	4.8	14.4	47.9
16	COM5	Banks/Financial Institutions	1.0	5.2	15.5	51.7
17	COM6	Hospital	1.0	5.1	15.4	51.3
18	COM7	Medical Office/Clinic	1.0	5.2	15.3	51.2
19	COM8	Entertainment & Recreation	1.1	5.4	16.3	54.4
20	COM9	Theaters	1.0	5.3	15.8	52.7
21	COM10	Parking	0.3	2.2	6.5	21.7
		Industrial				
22	IND1	Heavy	1.4	7.2	21.8	72.5
23	IND2	Light	1.4	7.2	21.8	72.5
24	IND3	Food/Drugs/Chemicals	1.4	7.2	21.8	72.5
25	IND4	Metals/Minerals Processing	1.4	7.2	21.8	72.5
26	IND5	High Technology	1.4	7.2	21.8	72.5
27	IND6	Construction	1.4	7.2	21.8	72.5
		Agriculture				
28	AGR1	Agriculture	0.8	4.6	13.8	46.1
		Religion/Non-Profit				
29	REL1	Church/Membership Organization	0.9	4.7	14.3	47.6
		Government				
30	GOV1	General Services	1.0	4.9	14.8	49.3
31	GOV2	Emergency Response	1.0	5.1	15.1	50.5
		Education				
32	EDU1	Schools/Libraries	0.7	3.2	9.7	32.4
33	EDU2	Colleges/Universities	0.6	2.9	8.7	29.0

Table 15.4: Drift Sensitive Non-structural Repair Costs
(in % of building replacement cost)

No.	Label	Occupancy Class	Drift Sensitive Non-structural Damage State			
			Slight	Moderate	Extensive	Complete
		Residential				
1	RES1	Single Family Dwelling	1.0	5.0	25.0	50.0
2	RES2	Mobile Home	0.8	3.8	18.9	37.8
3-8	RES3a-f	Multi Family Dwelling	0.9	4.3	21.3	42.5
9	RES4	Temporary Lodging	0.9	4.3	21.6	43.2
10	RES5	Institutional Dormitory	0.8	4.0	20.0	40.0
11	RES6	Nursing Home	0.8	4.1	20.4	40.8
		Commercial				
12	COM1	Retail Trade	0.6	2.7	13.8	27.5
13	COM2	Wholesale Trade	0.6	2.6	13.2	26.5
14	COM3	Personal and Repair Services	0.7	3.4	16.9	33.8
15	COM4	Professional/Technical/ Business Services	0.7	3.3	16.4	32.9
16	COM5	Banks/Financial Institutions	0.7	3.4	17.2	34.5
17	COM6	Hospital	0.8	3.5	17.4	34.7
18	COM7	Medical Office/Clinic	0.7	3.4	17.2	34.4
19	COM8	Entertainment & Recreation	0.7	3.6	17.8	35.6
20	COM9	Theaters	0.7	3.5	17.6	35.1
21	COM10	Parking	0.4	1.7	8.7	17.4
		Industrial				
22	IND1	Heavy	0.2	1.2	5.9	11.8
23	IND2	Light	0.2	1.2	5.9	11.8
24	IND3	Food/Drugs/Chemicals	0.2	1.2	5.9	11.8
25	IND4	Metals/Minerals Processing	0.2	1.2	5.9	11.8
26	IND5	High Technology	0.2	1.2	5.9	11.8
27	IND6	Construction	0.2	1.2	5.9	11.8
		Agriculture				
28	AGR1	Agriculture	0.0	0.8	3.8	7.7
		Religion/Non-Profit				
29	REL1	Church/Membership Organization	0.8	3.3	16.3	32.6
		Government				
30	GOV1	General Services	0.7	3.3	16.4	32.8
31	GOV2	Emergency Response	0.7	3.4	17.1	34.2
		Education				
32	EDU1	Schools/Libraries	0.9	4.9	24.3	48.7
33	EDU2	Colleges/Universities	1.2	6.0	30.0	60.0

Note that the values in the last column of Tables 15.2, 15.3 and 15.4 must sum to 100 since the complete damage state implies that the structure must be replaced. The replacement value of the structure is the sum of the structural and non-structural components.

15.2.1.2 Procedure for Updating Building Replacement Cost Estimates

The building replacement cost estimates were developed based on 2003 estimates. The historical cost indices provided in the Means publication can also be used to adjust costs (generally upwards) to the year in which the loss estimate is being implemented. (It will be necessary for the user to obtain access to the Means publication for the year of implementation.)

15.2.2 Building Contents Losses

Building contents are defined as furniture, equipment that is not integral with the structure, computers and other supplies. Contents do not include inventory or non-structural components (see Section 15.2.1) such as lighting, ceilings, mechanical and electrical equipment and other fixtures. It is assumed that most contents damage, such as overturned cabinets and equipment or equipment sliding off tables and counters, is a function of building accelerations. Therefore, acceleration sensitive non-structural damage is considered to be a good indicator of contents damage. That is, if there is no acceleration sensitive non-structural damage, it is unlikely that there will be contents damage. The cost of contents damage is calculated as follows:

$$CCD_i = CRV_i * \sum_{ds=2}^{5} CD_{ds,i} * PMBTNSA_{ds,j} \qquad (15\text{-}10)$$

where:

CCD_i	cost of contents damage for occupancy i
CRV_i	contents replacement value for occupancy i
$CD_{ds,i}$	contents damage ratio for occupancy i in damage state ds (from Table 15.5)
$PMBTNSA_{ds,j}$	the probability of occupancy i being in non-structural acceleration sensitive damage state ds, see Chapter 5

The contents damage ratios in Table 15.5 assume that at complete damage state some percentage of contents, set at 50%, can be retrieved. At the present time, contents damage percentages in Table 15. are the same for all occupancies.

Table 15.5: Contents Damage Ratios
(in % of contents replacement cost)

No.	Label	Occupancy Class	Acceleration Sensitive Non-structural Damage State			
			Slight	Moderate	Extensive	Complete*
		Residential				
1	RES1	Single Family Dwelling	1	5	25	50
2	RES2	Mobile Home	1	5	25	50
3-8	RES3a-f	Multi Family Dwelling	1	5	25	50
9	RES4	Temporary Lodging	1	5	25	50
10	RES5	Institutional Dormitory	1	5	25	50
11	RES6	Nursing Home	1	5	25	50
		Commercial				
12	COM1	Retail Trade	1	5	25	50
13	COM2	Wholesale Trade	1	5	25	50
14	COM3	Personal and Repair Services	1	5	25	50
15	COM4	Professional/Technical/ Business Services	1	5	25	50
16	COM5	Banks/Financial Institutions	1	5	25	50
17	COM6	Hospital	1	5	25	50
18	COM7	Medical Office/Clinic	1	5	25	50
19	COM8	Entertainment & Recreation	1	5	25	50
20	COM9	Theaters	1	5	25	50
21	COM10	Parking	1	5	25	50
		Industrial				
22	IND1	Heavy	1	5	25	50
23	IND2	Light	1	5	25	50
24	IND3	Food/Drugs/Chemicals	1	5	25	50
25	IND4	Metals/Minerals Processing	1	5	25	50
26	IND5	High Technology	1	5	25	50
27	IND6	Construction	1	5	25	50
		Agriculture				
28	AGR1	Agriculture	1	5	25	50
		Religion/Non-Profit				
29	REL1	Church/Membership Organization	1	5	25	50
		Government				
30	GOV1	General Services	1	5	25	50
31	GOV2	Emergency Response	1	5	25	50
		Education				
32	EDU1	Schools/Libraries	1	5	25	50
33	EDU2	Colleges/Universities	1	5	25	50

*At complete damage state, it is assumed that some salvage of contents will take place.

15.2.3 Business Inventory Losses

Business inventories vary considerably with occupancy. For example, the value of inventory for a high tech manufacturing facility would be very different from that of a retail store. Thus, it is assumed for this model that business inventory for each occupancy class is based on annual sales. Since losses to business inventory most likely occur from stacks of inventory falling over, objects falling off shelves, or from water damage when piping breaks, it is assumed, as it was with building contents, that acceleration sensitive non-structural damage is a good indicator of losses to business inventory. Business inventory losses then become the product of the total inventory value (floor area times the percent of gross sales or production per square foot) of buildings of a given occupancy in a given acceleration-sensitive damage state, the percent loss to the inventory and the probability of given damage states. The business inventory losses are given by the following expressions.

$$INV_i = FA_i * SALES_i * BI_i * \sum_{ds=2}^{5} PONSA_{ds,i} * INVD_{ds,i} \qquad (15\text{-}11)$$

$$INV = INV_7 + INV_8 + \sum_{i=17}^{23} INV_i \qquad (15\text{-}12)$$

where:

INV_i	value of inventory losses for occupancy i
INV	total value of inventory losses
FA_i	floor area of occupancy group i (in square feet)
$SALES_i$	annual gross sales or production (per square foot) for occupancy i (see Table 15.6)
BI_i	business inventory as a percentage of annual gross sales for occupancy i (i = 7, 8, 17-23, see Table 15.7)
$PONSA_{ds,i}$	probability of occupancy i being in non-structural acceleration sensitive damage state ds, see Chapter 5
$INVD_{ds,i}$	percent inventory damage for occupancy i in damage state ds (from Table 15.8)

Statistics representing national or state economic sectors may not adequately reflect the regional situation. Therefore, estimates of annual gross sales or the value of production for any one of the 28 economic sectors can vary widely depending on the type of firms that are located in the region. It is important to review and adjust any data to insure that the regional economy is correctly portrayed. Annual sales or production per square foot of building can be estimated by dividing the output-employment ratio (sector output/sector employment) by the average floor space occupied by employee. Current data to derive the regional (county or standard metropolitan statistical area), sector output-employment ratio is usually available from either the state or the U.S. Department of Commerce's Bureau of Economic Analysis [(202) 482-1986]. The annual sales per square foot for the agriculture category are for greenhouses. The average sector floor space occupied per employee is based on values found in ATC-13, table 4.7 (pages 94-97). Judgment was used in estimating of business inventory as a percent of gross annual sales.

Table 15.6: Annual Gross Sales or Production (Dollars per Square Foot)

No.	Label	Occupancy Class	1990 Output/ Employment*	Sq. ft. floor Space/Employee**	Annual Sales ($/ft^2)
		Commercial			
7	COM1	Retail Trade	$24,979	825	41
8	COM2	Wholesale Trade	$38,338	900	59
		Industrial			
17	IND1	Heavy	$220,212	550	551
18	IND2	Light	$74,930	590	175
19	IND3	Food/Drugs/Chemicals	$210,943	540	538
20	IND4	Metals/Minerals Processing	$268,385	730	507
21	IND5	High Technology	$73,517	300	337
22	IND6	Construction	$107,739	250	593
		Agriculture			
23	AGR1	Agriculture	$20,771	250	114

* Typical sector values.
** ATC-13, Table 4.7, pages 94-97 (ATC, 1985).

Table 15.7: Business Inventory (% of Gross Annual Sales)

No.	Label	Occupancy Class	Business Inventory (%)
		Commercial	
7	COM1	Retail Trade	13
8	COM2	Wholesale Trade	10
		Industrial	
17	IND1	Heavy	5
18	IND2	Light	4
19	IND3	Food/Drugs/Chemicals	5
20	IND4	Metals/Minerals Processing	3
21	IND5	High Technology	4
22	IND6	Construction	2
		Agriculture	
23	AGR1	Agriculture	8

Table 15.8: Percent Business Inventory Damage

No.	Label	Occupancy Class	Acceleration Sensitive Non-structural Damage State			
			Slight	**Moderate**	**Extensive**	**Complete***
		Commercial				
7	COM1	Retail Trade	1	5	25	50
8	COM2	Wholesale Trade	1	5	25	50
		Industrial				
17	IND1	Heavy	1	5	25	50
18	IND2	Light	1	5	25	50
19	IND3	Food/Drugs/Chemicals	1	5	25	50
20	IND4	Metals/Minerals Processing	1	5	25	50
21	IND5	High Technology	1	5	25	50
22	IND6	Construction	1	5	25	50
		Agriculture				
23	AGR1	Agriculture	1	5	25	50

*At complete damage state, it is assumed that some salvage of inventory will take place.

15.2.4 Building Repair Time/Loss of Function

The damage state descriptions provide a basis for establishing loss of function and repair time. A distinction should be made between loss of function and repair time. Here loss of function is the time that a facility is not capable of conducting business. This, in general, will be shorter than repair time because business will rent alternative space while repairs and construction are being completed. The time to repair a damaged building can be divided into two parts: construction and clean-up time, and time to obtain financing, permits and complete design. For the lower damage states, the construction time will be close to the real repair time. At the higher damage levels, a number of additional tasks must be undertaken that typically will considerably increase the actual repair time. These tasks, which may vary considerably in scope and time between individual projects, include:

- Decision-making (related to business of institutional constraints, plans, financial status, etc.)
- Negotiation with FEMA (for public and non-profit), SBA etc.
- Negotiation with insurance company, if insured
- Obtain financing
- Contract negotiation with design firms(s)
- Detailed inspections and recommendations
- Preparation of contract documents
- Obtain building and other permits
- Bid/negotiate construction contract
- Start-up and occupancy activities after construction completion

Building repair and clean-up times are presented in Table 15.9. These times represent estimates of the median time for actual cleanup and repair, or construction. These estimates are extended in Table 15.10 to account for delays in decision-making, financing, inspection etc., as outlined above, and represent estimates of the median time for recovery of building functions.

Table 15.9: Building Cleanup and Repair Time (Construction) (Time in Days)

No.	Label	Occupancy Class	Construction Time				
			Structural Damage State				
			None	Slight	Moderate	Extensive	Complete
		Residential					
1	RES1	Single Family Dwelling	0	2	30	90	180
2	RES2	Mobile Home	0	2	10	30	60
3-8	RES3a-f	Multi Family Dwelling	0	5	30	120	240
9	RES4	Temporary Lodging	0	5	30	120	240
10	RES5	Institutional Dormitory	0	5	30	120	240
11	RES6	Nursing Home	0	5	30	120	240
		Commercial					
12	COM1	Retail Trade	0	5	30	90	180
13	COM2	Wholesale Trade	0	5	30	90	180
14	COM3	Personal and Repair Services	0	5	30	90	180
15	COM4	Professional/Technical/ Business Services	0	5	30	120	240
16	COM5	Banks/Financial Institutions	0	5	30	90	180
17	COM6	Hospital	0	10	45	180	360
18	COM7	Medical Office/Clinic	0	10	45	180	240
19	COM8	Entertainment & Recreation	0	5	30	90	180
20	COM9	Theaters	0	5	30	120	240
21	COM10	Parking	0	2	20	80	160
		Industrial					
22	IND1	Heavy	0	10	30	120	240
23	IND2	Light	0	10	30	120	240
24	IND3	Food/Drugs/Chemicals	0	10	30	120	240
25	IND4	Metals/Minerals Processing	0	10	30	120	240
26	IND5	High Technology	0	20	45	180	360
27	IND6	Construction	0	5	20	80	160
		Agriculture					
28	AGR1	Agriculture	0	2	10	30	60
		Religion/Non-Profit					
29	REL1	Church/Membership Organization	0	10	30	120	240
		Government					
30	GOV1	General Services	0	10	30	120	240
31	GOV2	Emergency Response	0	5	20	90	180
		Education					
32	EDU1	Schools/Libraries	0	10	30	120	240
33	EDU2	Colleges/Universities	0	10	45	180	360

Table 15.10: Building Recovery Time
(Time in Days)

No.	Label	Occupancy Class	Recovery Time				
			Structural Damage State				
			None	Slight	Moderate	Extensive	Complete
		Residential					
1	RES1	Single Family Dwelling	0	5	120	360	720
2	RES2	Mobile Home	0	5	20	120	240
3-8	RES3a-f	Multi Family Dwelling	0	10	120	480	960
9	RES4	Temporary Lodging	0	10	90	360	480
10	RES5	Institutional Dormitory	0	10	90	360	480
11	RES6	Nursing Home	0	10	120	480	960
		Commercial					
12	COM1	Retail Trade	0	10	90	270	360
13	COM2	Wholesale Trade	0	10	90	270	360
14	COM3	Personal and Repair Services	0	10	90	270	360
15	COM4	Professional/Technical/ Business Services	0	20	90	360	480
16	COM5	Banks/Financial Institutions	0	20	90	180	360
17	COM6	Hospital	0	20	135	540	720
18	COM7	Medical Office/Clinic	0	20	135	270	540
19	COM8	Entertainment & Recreation	0	20	90	180	360
20	COM9	Theaters	0	20	90	180	360
21	COM10	Parking	0	5	60	180	360
		Industrial					
22	IND1	Heavy	0	10	90	240	360
23	IND2	Light	0	10	90	240	360
24	IND3	Food/Drugs/Chemicals	0	10	90	240	360
25	IND4	Metals/Minerals Processing	0	10	90	240	360
26	IND5	High Technology	0	20	135	360	540
27	IND6	Construction	0	10	60	160	320
		Agriculture					
28	AGR1	Agriculture	0	2	20	60	120
		Religion/Non-Profit					
29	REL1	Church/Membership Organization	0	5	120	480	960
		Government					
30	GOV1	General Services	0	10	90	360	480
31	GOV2	Emergency Response	0	10	60	270	360
		Education					
32	EDU1	Schools/Libraries	0	10	90	360	480
33	EDU2	Colleges/Universities	0	10	120	480	960

Repair times differ for similar damage states depending on building occupancy: thus simpler and smaller buildings will take less time to repair than more complex, heavily serviced or larger buildings. It has also been noted that large well-financed corporations can sometimes accelerate the repair time compared to normal construction procedures.

However, establishment of a more realistic repair time does not translate directly into business or service interruption. For some businesses, building repair time is largely irrelevant, because these businesses can rent alternative space or use spare industrial/commercial capacity elsewhere. These factors are reflected in Table 15.11, which provides multipliers to be applied to the values in Table 15.10 to arrive at estimates of business interruption for economic purposes. The factors in Tables 15.9, 15.10, and 15.11 are judgmentally derived, using ATC-13, Table 9.11 as a starting point.

The times resulting from the application of the Table 15.11 multipliers to the times shown in Table 15.10 represent median values for the probability of business or service interruption. For none and slight damage the time loss is assumed to be short, with cleanup by staff, but work can resume while slight repairs are done. For most commercial and industrial businesses that suffer moderate or extensive damage, the business interruption time is shown as short on the assumption that these concerns will find alternate ways of continuing their activities. The values in Table15.11 also reflect the fact that a proportion of business will suffer longer outages or even fail completely. Church and Membership Organizations generally quickly find temporary accommodation, and government offices also resume operating almost at once. It is assumed that hospitals and medical offices can continue operating, perhaps with some temporary rearrangement and departmental relocation if necessary, after moderate damage, but with extensive damage their loss of function time is also assumed to be equal to the total time for repair.

For other businesses and facilities, the interruption time is assumed to be equal to, or approaching, the total time for repair. This applies to residential, entertainment, theaters, parking, and religious facilities whose revenue or continued service, is dependent on the existence and continued operation of the facility.

The modifiers from Table 15.11 are multiplied by extended building construction times as follows:

$$LOF_{ds} = BCT_{ds} * MOD_{ds} \tag{15-13}$$

where:

LOF_{ds} loss of function for damage state ds

BCT_{ds} building construction and clean up time for damage state ds (See Table 15.10)

MOD_{ds} construction time modifiers for damage state ds (See Table 15.11)

The median value applies to a large inventory of facilities. Thus, at moderate damage, some marginal businesses may close, while others will open after a day's cleanup. Even with extensive damage, some businesses will accelerate repair, while a number will also close or be demolished. For example, one might reasonably assume that a URM building that suffers moderate damage is more likely to be demolished than a newer building that suffers moderate, or even, extensive damage. If the URM building is an historic structure its likelihood of survival and repair will probably increase. There will also be a small number of extreme cases: the slightly damaged building that becomes derelict, or the extensively damaged building that continues to function for years, with temporary shoring, until an expensive repair is financed and executed.

Table 15.11: Building and Service Interruption Time Multipliers

No.	Label	Occupancy Class	Construction Time				
			Structural Damage State				
			None	Slight	Moderate	Extensive	Complete
		Residential					
1	RES1	Single Family Dwelling	0	0	0.5	1.0	1.0
2	RES2	Mobile Home	0	0	0.5	1.0	1.0
3-8	RES3a-f	Multi Family Dwelling	0	0	0.5	1.0	1.0
9	RES4	Temporary Lodging	0	0	0.5	1.0	1.0
10	RES5	Institutional Dormitory	0	0	0.5	1.0	1.0
11	RES6	Nursing Home	0	0	0.5	1.0	1.0
		Commercial					
12	COM1	Retail Trade	0.5	0.1	0.1	0.3	0.4
13	COM2	Wholesale Trade	0.5	0.1	0.2	0.3	0.4
14	COM3	Personal and Repair Services	0.5	0.1	0.2	0.3	0.4
15	COM4	Professional/Technical/ Business Services	0.5	0.1	0.1	0.2	0.3
16	COM5	Banks/Financial Institutions	0.5	0.1	0.05	0.03	0.03
17	COM6	Hospital	0.5	0.1	0.5	0.5	0.5
18	COM7	Medical Office/Clinic	0.5	0.1	0.5	0.5	0.5
19	COM8	Entertainment & Recreation	0.5	0.1	1.0	1.0	1.0
20	COM9	Theaters	0.5	0.1	1.0	1.0	1.0
21	COM10	Parking	0.1	0.1	1.0	1.0	1.0
		Industrial					
22	IND1	Heavy	0.5	0.5	1.0	1.0	1.0
23	IND2	Light	0.5	0.1	0.2	0.3	0.4
24	IND3	Food/Drugs/Chemicals	0.5	0.2	0.2	0.3	0.4
25	IND4	Metals/Minerals Processing	0.5	0.2	0.2	0.3	0.4
26	IND5	High Technology	0.5	0.2	0.2	0.3	0.4
27	IND6	Construction	0.5	0.1	0.2	0.3	0.4
		Agriculture					
28	AGR1	Agriculture	0	0	0.05	0.1	0.2
		Religion/Non-Profit					
29	REL1	Church/Membership Organization	1	0.2	0.05	0.03	0.03
		Government					
30	GOV1	General Services	0.5	0.1	0.02	0.03	0.03
31	GOV2	Emergency Response	0.5	0.1	0.02	0.03	0.03
		Education					
32	EDU1	Schools/Libraries	0.5	0.1	0.02	0.05	0.05
33	EDU2	Colleges/Universities	0.5	0.1	0.02	0.03	0.03

15.2.5 Relocation Expenses

Relocation costs may be incurred when the level of building damage is such that the building or portions of the building are unusable while repairs are being made. While relocation costs may include a number of expenses, in this model, only the following components are considered: **disruption costs** that include the cost of shifting and transferring, and the **rental** of temporary space. It should be noted that the burden of relocation expenses are not expected to be borne by the renter. Instead it is assumed that the building owners will incur the expense of moving their tenants to a new location. It should also be noted that a renter who has been displaced from a property due to earthquake damage would cease to pay rent to the owner of the damaged property and only pay rent to the new landlord. Therefore, the renter has no new rental expenses. It is assumed that the owner of the damaged property will pay the disruption costs for his renter. If the damaged property is owner occupied, then the owner will have to pay for disruption costs in addition to the cost of rent while he is repairing his building.

It is assumed in this model that it is unlikely that an occupant will relocate if a building is in the damage states none or slight. The exceptions are some government or emergency response services that need to be operational immediately after an earthquake. However these are considered to contribute very little to the total relocation expenses for a region and are ignored. Finally, it is assumed that entertainment, theaters, parking facilities and heavy industry (occupancy classes 19 to 22) will not relocate to new facilities. Instead they will resume operation when their facilities have been repaired or replaced. Relocation expenses are then a function of the floor area, the rental costs per day per square foot, a disruption cost, the expected days of loss of function for each damage state, the type of occupancy and the damage state itself. These are given by the following expression.

$$\mathrm{REL_i} = \mathrm{FA_i} * \begin{bmatrix} (1-\%OO_i) * \sum_{ds=3}^{5} (POSTR_{ds,i} * DC_i) + \\ \%OO_i * \sum_{ds=3}^{5} (POSTR_{ds,i} * (DC_i + RENT_i * RT_{ds})) \end{bmatrix} \tag{15-14}$$

where:

REL_i	relocation costs for occupancy class i (i = 1-18 and 23-33)
FA_i	floor area of occupancy class i (in square feet)
$POSTR_{ds,i}$	probability of occupancy class i being in structural damage state ds
DC_i	disruption costs for occupancy i ($\$/ft^2$, See Table 15.12)
RT_{ds}	recovery time for damage state ds (See Table 15.10)
%OO	percent owner occupied for occupancy i (See Table 15.13)
$RENT_i$	rental cost ($\$/ft^2/day$) for occupancy i (See Table 15.12)

The default values for rental costs and disruption costs are 1994 values. However, actual values will vary from region to region; local numbers should be substituted for the default values. Regional numbers are commonly available from Chambers of Commerce or state and/or local regional economic development agencies.

Table 15.12: Rental Costs and Disruption Costs

#	Label	Occupancy Class	Rental Cost ($\$/ft^2$/month)	Disruption Costs ($\$/ft^2$)
		Residential		
1	RES1	Single Family Dwelling	0.68	0.82
2	RES2	Mobile Home	0.48	0.82
3-8	RES3a-f	Multi Family Dwelling	0.61	0.82
9	RES4	Temporary Lodging	2.04	0.82
10	RES5	Institutional Dormitory	0.41	0.82
11	RES6	Nursing Home	0.75	0.82
		Commercial		
12	COM1	Retail Trade	1.16	1.09
13	COM2	Wholesale Trade	0.48	0.95
14	COM3	Personal and Repair Services	1.36	0.95
15	COM4	Professional/Technical/ Business Services	1.36	0.95
16	COM5	Banks	1.70	0.95
17	COM6	Hospital	1.36	1.36
18	COM7	Medical Office/Clinic	1.36	1.36
19	COM8	Entertainment & Recreation	1.70	N/A
20	COM9	Theaters	1.70	N/A
21	COM10	Parking	0.34	N/A
		Industrial		
22	IND1	Heavy	0.20	N/A
23	IND2	Light	0.27	0.95
24	IND3	Food/Drugs/Chemicals	0.27	0.95
25	IND4	Metals/Minerals Processing	0.20	0.95
26	IND5	High Technology	0.34	0.95
27	IND6	Construction	0.14	0.95
		Agriculture		
28	AGR1	Agriculture	0.68	0.68
		Religion/Non/Profit		
29	REL1	Church/Membership Organization	1.02	0.95
		Government		
30	GOV1	General Services	1.36	0.95
31	GOV2	Emergency Response	1.36	0.95
		Education		
32	EDU1	Schools/Libraries	1.02	0.95
33	EDU2	Colleges/Universities	1.36	0.95

Table 15.13: Percent Owner Occupied

No.	Label	Occupancy Class	Percent Owner Occupied
		Residential	
1	RES1	Single Family Dwelling	75
2	RES2	Mobile Home	85
3-8	RES3a-f	Multi Family Dwelling	35
9	RES4	Temporary Lodging	0
10	RES5	Institutional Dormitory	0
11	RES6	Nursing Home	0
		Commercial	
12	COM1	Retail Trade	55
13	COM2	Wholesale Trade	55
14	COM3	Personal and Repair Services	55
15	COM4	Professional/Technical/ Business Services	55
16	COM5	Banks	75
17	COM6	Hospital	95
18	COM7	Medical Office/Clinic	65
19	COM8	Entertainment & Recreation	55
20	COM9	Theaters	45
21	COM10	Parking	25
		Industrial	
22	IND1	Heavy	75
23	IND2	Light	75
24	IND3	Food/Drugs/Chemicals	75
25	IND4	Metals/Minerals Processing	75
26	IND5	High Technology	55
27	IND6	Construction	85
		Agriculture	
28	AGR1	Agriculture	95
		Religion/Non/Profit	
29	REL1	Church/Membership Organization	90
		Government	
30	GOV1	General Services	70
31	GOV2	Emergency Response	95
		Education	
32	EDU1	Schools/Libraries	95
33	EDU2	Colleges/Universities	90

15.2.6 Loss of Income

Business activity generates several types of income. First is income associated with capital, or property ownership. Business generates profits, and a portion of this is paid out to individuals (as well as to pension funds and other businesses) as dividends, while another portion, retained earnings, is plowed back into the enterprise. Businesses also make interest payments to banks and bondholders for loans. They pay rental income on property and make royalty payments for the use of tangible assets. Those in business for themselves, or in partnerships, generate a category called proprietary income, one portion of which reflects their profits and the other that reflects an imputed salary (e.g., the case of lawyers or dentists). Finally, the biggest category of income generated/paid is associated with labor. In most urban regions of the U.S., wage and salary income comprises more than 75% of total personal income payments.

It is possible to link income payments to various physical damage measures including sales, property values, and square footage. The latter approach is used here. Income losses occur when building damage disrupts economic activity. Income losses are the product of floor area, income realized per square foot and the expected days of loss of function for each damage state. Proprietor’s income losses are expressed as follows:

$$YLOS_i = (1\text{-}RF_i)*FA_i*INC_i*\sum_{ds=1}^{5} POSTR_{ds,i} * LOF_{ds} \tag{15-15}$$

where:

$YLOS_i$	income losses for occupancy class i
FA_i	floor area of occupancy class i (in square feet)
INCi	income per day (per square foot) for occupancy class i (Table 15.15)
$POSTR_{ds,i}$	probability of occupancy i being in structural damage state ds,
LOF_{ds}	loss of function time for damage state ds (see Equation 15-13)
RF_i	recapture factor for occupancy i (Table 15.14)

National estimates of sectoral income were obtained from the IMPLAN System, which in turn is based on U.S. Department of Commerce Bureau of Analysis data. The income data used was a three-year average to dampen cyclical variations especially prevalent for profit-related income. Income per square foot of floor space can then be derived by dividing income by the floor space occupied by a specific sector. As with losses and costs discussed above, income will vary considerably depending on regional economic conditions. Therefore, default values need to be adjusted for local conditions. Default values for floor space were derived from information in Table 4.7 of ATC-13.

15.2.6.1 Recapture Factors

The business-related losses from earthquakes can be recouped to some extent by working overtime after the event. For example, a factory that is closed for six weeks due to directly-caused structural damage or indirectly-caused shortage of supplies may work extra shifts in the weeks or months following its reopening. It is necessary that there be a demand for its output (including inventory buildup), but this is likely to be the case as undamaged firms try to overcome input shortages, other firms that were temporarily closed try to make-up their lost production as well, and firms outside the region press for resumption of export sales to them.

Table 15.14: Recapture Factors

Occupancy	Wage Recapture (%)	Employment Recapture (%)	Income Recapture (%)	Output Recapture (%)
RES1	0	0	0	0
RES2	0	0	0	0
RES3a-f	0	0	0	0
RES4	0.60	0.60	0.60	0.60
RES5	0.60	0.60	0.60	0.60
RES6	0.60	0.60	0.60	0.60
COM1	0.87	0.87	0.87	0.87
COM2	0.87	0.87	0.87	0.87
COM3	0.51	0.51	0.51	0.51
COM4	0.90	0.90	0.90	0.90
COM5	0.90	0.90	0.90	0.90
COM6	0.60	0.60	0.60	0.60
COM7	0.60	0.60	0.60	0.60
COM8	0.60	0.60	0.60	0.60
COM9	0.60	0.60	0.60	0.60
COM10	0.60	0.60	0.60	0.60
IND1	0.98	0.98	0.98	0.98
IND2	0.98	0.98	0.98	0.98
IND3	0.98	0.98	0.98	0.98
IND4	0.98	0.98	0.98	0.98
IND5	0.98	0.98	0.98	0.98
IND6	0.95	0.95	0.95	0.95
AGR1	0.75	0.75	0.75	0.75
REL1	0.60	0.60	0.60	0.60
GOV1	0.80	0.80	0.80	0.80
GOV2	0	0	0	0
EDU1	0.60	0.60	0.60	0.60
EDU2	0.60	0.60	0.60	0.60

Obviously, this ability to “recapture” production will differ across industries. It will be high for those that produce durable output and lower for those that produce perishables or “spot” products (examples of the latter being utility sales to residential customers, hotel services, entertainment). Even some durable manufacturing enterprises would seem to have severe recapture limits because they already work three shifts per day; however, work on weekends, excess capacity, and temporary production facilities all can be used to make up lost sales.

The following table presents a set of recapture factors for the economic sectors used in the direct loss module. They are deemed appropriate for business disruptions lasting up to three months. As lost production becomes larger, it is increasingly difficult to recapture it for both demand-side and supply-side reasons. For more advanced studies, users may choose to adjust recapture factors downward for longer disruptions.

15.2.7 Rental Income Losses

Rental income losses are the product of floor area, rental rates per sq. ft. and the expected days of loss of function for each damage state. Rental income losses include residential, commercial and industrial properties. It is assumed that a renter will pay full rent if the property is in the damage state none or slight. Thus rental income losses are calculated only for damage states 3, 4 and 5. It should be noted that rental income is based upon the percentage of floor area in occupancy i that is being rented (1 - $\%OO_i$).

$$RY_i = (1\text{-}\%OO_i) * FA_i * RENT_i * \sum_{ds=3}^{5} POSTR_{ds,i} * RT_{ds} \qquad (15\text{-}16)$$

where:

RY_i	rental income losses for occupancy i
$\%OO_i$	percent owner occupied for occupancy i (See Table 15.13)
FA_i	floor area of occupancy group i (in square feet)
$RENT_i$	rental cost ($\$/ft^2/day$) for occupancy i (See Table 15.12)
$POSTR_{ds,I}$	probability of occupancy i being in structural damage state ds, see Chapter 5
RT_{ds}	recovery time for damage state ds (See Table 15.10)

Rental rates vary widely with region and depend on local economic conditions including vacancy rate, the desirability of the neighborhood, and the desirability of the buildings. Regional and city rental rates are published annually by various real estate information services. The percentage rates given for owner occupancy are judgmentally based. For a given study region, census data will provide a more accurate measure for residential numbers.

15.2.8 Guidance for Estimate Using Advanced Data and Models Analysis

The methodological framework shown for the Default and User-Supplied Data Analyses will still apply for this type of analysis. However, depending on the type of analysis required, much more detailed inventory and cost information can be obtained from consultants. In the area of cost, professional building cost consultants maintain detailed records of costs and trends, and have knowledge of local building practices that might affect a loss estimate. Inventory improvement might include substantial "windshield" surveys that can greatly augment the accuracy of building type and occupancy information. It should be noted that while the windshield survey has limitations in procuring detailed information on structural types it is effective in procuring the kind of size and occupancy information necessary for the generic cost estimating proposed in this methodology.

Table 15.15: Proprietor's Income

#	Label	Occupancy Class	Income		Wages per Square Foot per Day	Employees per Square Foot	Output per Square Foot per Day
			per Square Foot per Year	per Square Foot per Day			
		Residential					
1	RES1	Single Family Dwelling	0.000	0.000	0.000	0.000	0.000
2	RES2	Mobile Home	0.000	0.000	0.000	0.000	0.000
3-8	RES3a-f	Multi Family Dwelling	0.000	0.000	0.000	0.000	0.000
9	RES4	Temporary Lodging	32.065	0.088	0.206	0.003	0.46
10	RES5	Institutional Dormitory	0.000	0.000	0.000	0.000	0.000
11	RES6	Nursing Home	53.442	0.146	0.345	0.005	0.767
		Commercial					
12	COM1	Retail Trade	19.785	0.054	0.189	0.004	0.401
13	COM2	Wholesale Trade	32.449	0.089	0.233	0.002	0.521
14	COM3	Personal and Repair Services	42.754	0.117	0.276	0.004	0.614
15	COM4	Professional/Technical/ Business Services	336.882	0.923	0.328	0.004	0.897
16	COM5	Banks	384.421	1.053	0.534	0.006	2.912
17	COM6	Hospital	53.442	0.146	0.345	0.005	0.767
18	COM7	Medical Office/Clinic	106.884	0.293	0.689	0.01	1.534
19	COM8	Entertainment & Recreation	196.013	0.537	0.427	0.007	0.967
20	COM9	Theaters	64.13	0.176	0.414	0.006	0.921
21	COM10	Parking	0	0	0	0	0
		Industrial					
22	IND1	Heavy	81.098	0.222	0.368	0.003	1.555
23	IND2	Light	81.098	0.222	0.368	0.003	1.555
24	IND3	Food/Drugs/Chemicals	108.131	0.296	0.492	0.004	2.073
25	IND4	Metals/Minerals Processing	245.687	0.673	0.38	0.003	1.645
26	IND5	High Technology	162.196	0.444	0.737	0.006	3.109
27	IND6	Construction	79.065	0.217	0.398	0.005	1.54
		Agriculture					
28	AGR1	Agriculture	75.031	0.206	0.081	0.004	0.767
		Religion/Non/Profit					
29	REL1	Church/Membership Organization	42.754	0.117	0.276	0.004	1.534
		Government					
30	GOV1	General Services	35.112	0.096	2.646	0.025	0.614
31	GOV2	Emergency Response	0	0	4.023	0.038	0.705
		Education					
32	EDU1	Schools/Libraries	53.442	0.146	0.345	0.005	2.973
33	EDU2	Colleges/Universities	106.884	0.293	0.689	0.01	4.518

15.3 Description of Methodology: Lifelines

This section describes the methodologies used to estimate lifeline related direct economic losses. Direct physical damage to transportation and utility lifelines was discussed in Chapters 7 and 8, respectively. Estimation of direct economic losses for the extended network lifelines such as highways, railroads, water supply, and power supply, depends on the inventory data providing the location of all nodes and links, and the models relating ground motions to damage.

Direct economic losses are computed based on (1) probabilities of being in a certain damage state ($P[D_S \geq ds_i]$), (2) the replacement value of the component, and (3) damage ratios (DR_i) for each damage state, ds_i. Economic losses are evaluated by multiplying the compounded damage ratio (DR_C) by the replacement value. The compounded damage ratio is computed as the probabilistic combination of damage ratios as follows.

$$DR_c = \sum_{i=2}^{5} DR_i \text{ x } P[ds_i] \qquad (15\text{-}17)$$

where $P[ds_i]$ is the probability of being in damage state i, and 1, 2, 3, 4 and 5 are associated with damage states none, slight, moderate, extensive and complete. No losses are associated with damage state 1, therefore, the summation is from i = 2 to 5.

The probability of being in or exceeding a certain damage state ($P[D_S > ds_i$ | PGA, PGV or PGD]), for each component, were presented in Chapter 7 and Chapter 8. The probabilities of being in a particular damage state are as follows:

$$P[D_s = ds_1|\text{PGA or PGD}] = 1 - P[D_s \geq ds_2 \mid \text{PGA or PGD}] = \mathbf{P_1} \qquad (15\text{-}18)$$

$$P[D_s = ds_2|\text{PGA or PGD}] = P[D_s \geq ds_2 \mid \text{PGA or PGD}] - P[D_s \geq ds_3 \mid \text{PGA or PGD}] = \mathbf{P_2} \qquad (15\text{-}19)$$

$$P[D_s = ds_3|\text{PGA or PGD}] = P[D_s \geq ds_3 \mid \text{PGA or PGD}] - P[D_s \geq ds_4 \mid \text{PGA or PGD}] = \mathbf{P_3} \qquad (15\text{-}20)$$

$$P[D_s = ds_4|\text{PGA or PGD}] = P[D_s \geq ds_4 \mid \text{PGA or PGD}] - P[D_s \geq ds_5 \mid \text{PGA or PGD}] = \mathbf{P_4} \qquad (15\text{-}21)$$

$$P[D_s = ds_5|\text{PGA or PGD}] = P[D_s \geq ds_5 \mid \text{PGA or PGD}] = \mathbf{P_5} \qquad (15\text{-}22)$$

The estimates of replacement values of all lifeline system components are given in Tables 15.16 and 15.17. Table 15.16 provides the replacement values for the components of the transportation system, while Table 15.17 provides the replacement values for the utility system components. Most of the replacement value data comes from ATC-13 and ATC-25. These values are rough estimates and should only be used as a guide. It is expected that that user will input replacement values based on specific knowledge of the lifeline components in the study area. In cases where a range is given in Tables 15.16 and 15.17, the default value is set equal to the midpoint of the range.

Table 15.16: Default Replacement Values of Transportation System Components

System	Replacement Value (thous. $)	Label	Component Classification
Highway	10,000	HRD1	Major Roads (value based on one km length, 4 lanes)
	5,000	HRD2	Urban Streets (value based on one km length, 2 lanes)
	20,000	HWB1/HWB2	Major Bridges
	5,000	HWB8, 9, 10, 11, 15, 16, 20, 21, 22, 23, 26, 27	Continuous Bridges
	1,000	HWB3, 4, 5, 6, 7, 12, 13, 14, 17, 18, 19, 24, 25, 28	Other Bridges
	20,000	HTU1	Highway Bored/Drilled Tunnel (value based on liner)
	20,000	HTU2	Highway Cut and Cover Tunnel (value based on liner)
Rail	1,500	RTR1	Rail Track (value based on one km length)
	5,000	RBR1	Rail Bridge - Seismically Designed
	5,000	RBR2	Rail Bridge - Conventionally Designed
	10,000	RTU1	Rail Bored/Drilled Tunnel (value based on liner)
	10,000	RTU2	Rail Cut and Cover Tunnel (value based on liner)
	2,000	RST1	Rail Urban Station (C2L)
	2,000	RST2	Rail Urban Station (S2L)
	2,000	RST3	Rail Urban Station (S1L)
	2,000	RST4	Rail Urban Station (S5L)
	2,000	RST5	Rail Urban Station (PC1)
	2,000	RST6	Rail Urban Station (C3L)
	2,000	RST7	Rail Urban Station (W1L)
	3,000	RFF1	Rail Fuel Facility w/ Anchored Tanks, w/ BU Power
	3,000	RFF2	Rail Fuel Facility w/ Anchored Tanks, wo/ BU Power
	3,000	RFF3	Rail Fuel Facility w/ Unanchored Tanks, w/ BU Power
	3,000	RFF4	Rail Fuel Facility w/ Unanchored Tanks, wo/ BU Power
	3,000	RFF5	Rail Fuel Facility w/ Buried Tanks
	3,000	RDF1	Rail Dispatch Facility w/ Anchored Sub-Comp., w/ BU Power
	3,000	RDF2	Rail Dispatch Facility w/ Anchored Sub-Comp., wo/ BU Power
	3,000	RDF3	Rail Dispatch Facility w/ Unanchored Sub-Comp., w/ BU Power
	3,000	RDF4	Rail Dispatch Facility w/ Unanchored. Sub-Comp., w/0 BU Power
	2,800	RMF1	Rail Maintenance Facility (C2L)
	2,800	RMF2	Rail Maintenance Facility (S2L)
	2,800	RMF3	Rail Maintenance Facility (S1L)
	2,800	RMF4	Rail Maintenance Facility (S5L)
	2,800	RMF5	Rail Maintenance Facility (PC1)
	2,800	RMF6	Rail Maintenance Facility (C3L)
	2,800	RMF7	Rail Maintenance Facility (W1)

Table 15.16: Default Replacement Values of Transportation System Components (con't)

System	Replacement Value (thous $)	Label	Component Classification
Light Rail	1,500	LTR1	Light Rail Track
	5,000	LBR1	Light Rail Bridge - Seismically Designed/Retrofitted
	5,000	LBR2	Light Rail Bridge - Conventionally Designed
	10,000	LTU1	Light Rail Bored/Drilled Tunnel (value based on liner)
	10,000	LTU2	Light Rail Cut and Cover Tunnel (value based on liner)
	2,000	LDC1	Light Rail DC Substation w/ Anchored Sub-Components
	2,000	LDC2	Light Rail DC Substation w/ Unanchored Sub-Comp.
	3,000	LDF1	Lt Rail Dispatch Fac w/ Anchored Sub-Comp., w/ BU Power
	3,000	LDF2	Lt Rail Dispatch Fac w/ Anchored Sub-Comp., wo/ BU Power
	3,000	LDF3	Lt Rail Dispatch Fac w/ Unanchored Sub-Comp., w/ BU Power
	3,000	LDF4	Lt Rail Dispatch Fac w/ Unanchored Sub-Comp., wo/ BU Power
	2,600	LMF1	Light Rail Maintenance Facility (C2L)
	2,600	LMF2	Light Rail Maintenance Facility (S2L)
	2,600	LMF3	Light Rail Maintenance Facility (S1L)
	2,600	LMF4	Light Rail Maintenance Facility (S5L)
	2,600	LMF5	Light Rail Maintenance Facility (PC1)
	2,600	LMF6	Light Rail Maintenance Facility (C3L)
	2,600	LMF7	Light Rail Maintenance Facility (W1)
Bus	1,000	BPT1	Bus Urban Station (C2L)
	1,000	BPT2	Bus Urban Station (S2L)
	1,000	BPT3	Bus Urban Station (S1L)
	1,000	BPT4	Bus Urban Station (S5L)
	1,000	BPT5	Bus Urban Station (PC1)
	1,000	BPT6	Bus Urban Station (C3L)
	1,000	BPT7	Bus Urban Station (W1)
	150	BFF1	Bus Fuel Facility w/ Anchored Tanks, w/ BU Power
	150	BFF2	Bus Fuel Facility w/ Anchored Tanks, wo/ BU Power
	150	BFF3	Bus Fuel Facility w/ Unanchored Tanks, w/ BU Power
	150	BFF4	Bus Fuel Facility w/ Unanchored Tanks, wo/ BU Power
	150	BFF5	Bus Fuel Facility w/ Buried Tanks
	400	BDF1	Bus Dispatch Fac. w/ Anchored. Sub-Comp., w/ BU Power
	400	BDF2	Bus Dispatch Fac. w/ Anchored. Sub-Comp., wo/ BU Power
	400	BDF3	Bus Dispatch Fac. w/ Unanchored. Sub-Comp., w/ BU Power
	400	BDF4	Bus Dispatch Fac. w/ Unanchored. Sub-Comp., wo/ BU Power
	1,300	BMF1	Bus Maintenance Facility (C2L)
	1,300	BMF2	Bus Maintenance Facility (S2L)
	1,300	BMF3	Bus Maintenance Facility (S1L)
	1,300	BMF4	Bus Maintenance Facility (S5L)
	1,300	BMF5	Bus Maintenance Facility (PC1)
	1,300	BMF6	Bus Maintenance Facility (C3L)
	1,300	BMF7	Bus Maintenance Facility (W1)

Table 15.16: Default Replacement Values of Transportation System Components (con't)

System	Replacement Value (thous $)	Label	Component Classification
Port	1,500	PWS1	Port Waterfront Structures
	2,000	PEQ1	Anchored Port Handling Equipment
	2,000	PEQ2	Unanchored Port Handling Equipment
	1,200	PWH1	Port Warehouses (C2L)
	1,200	PWH2	Port Warehouses (S2L)
	1,200	PWH3	Port Warehouses (S1L)
	1,200	PWH4	Port Warehouses (S5L)
	1,200	PWH5	Port Warehouses (PC1)
	1,200	PWH6	Port Warehouses (C3L)
	1,200	PWH7	Port Warehouses (W1)
	2,000	PFF1	Port Fuel Facility w/ Anchored Tanks, w/ BU Power
	2,000	PFF2	Port Fuel Facility w/ Anchored Tanks, wo/ BU Power
	2,000	PFF3	Port Fuel Facility w/ Unanchored Tanks, w/ BU Power
	2,000	PFF4	Port Fuel Facility w/ Unanchored Tanks, wo/ BU Power
	2,000	PFF5	Port Fuel Facility w/ Buried Tanks
Ferry	1,500	FWS1	Ferry Waterfront Structures (Value for 7,500 ft^2 facility)
	1,000	FPT1	Ferry Passenger Terminals (C2L)
	1,000	FPT2	Ferry Passenger Terminals (S2L)
	1,000	FPT3	Ferry Passenger Terminals (S1L)
	1,000	FPT4	Ferry Passenger Terminals (S5L)
	1,000	FPT5	Ferry Passenger Terminals (PC1)
	1,000	FPT6	Ferry Passenger Terminals (C3L)
	1,000	FPT7	Ferry Passenger Terminals (W1)
	400	FFF1	Ferry Fuel Facility w/ Anchored Tanks, w/ BU Power
	400	FFF2	Ferry Fuel Facility w/ Anchored Tanks, wo/ BU Power
	400	FFF3	Ferry Fuel Facility w/ Unanchored Tanks, w/ BU Power
	400	FFF4	Ferry Fuel Facility w/ Unanchored Tanks, wo/ BU Power
	400	FFF5	Ferry Fuel Facility w/ Buried Tanks
	200	FDF1	Ferry Dispatch Fac. w/ Anchored. Sub-Comp., w/ BU Power
	200	FDF2	Ferry Dispatch Fac. w/ Anchored. Sub-Comp., wo/ BU Power
	200	FDF3	Ferry Dispatch Fac. w/ Unanchored. Sub-Comp., w/ BU Power
	200	FDF4	Ferry Dispatch Fac. w/ Unanchored. Sub-Comp., wo/ BU Power
	520	FMF1	Ferry Maintenance Facility (C2L)
	520	FMF2	Ferry Maintenance Facility (S2L)
	520	FMF3	Ferry Maintenance Facility (S1L)
	520	FMF4	Ferry Maintenance Facility (S5L)
	520	FMF5	Ferry Maintenance Facility (PC1)
	520	FMF6	Ferry Maintenance Facility (C3L)
	520	FMF7	Ferry Maintenance Facility (W1)

Table 15.16: Default Replacement Values of Transportation System Components (con't)

System	Replacement Value (thous $)	Label	Component Classification
Airport	5,000	ACT1	Airport Control Towers (C2L)
	5,000	ACT2	Airport Control Towers (S2L)
	5,000	ACT3	Airport Control Towers (S1L)
	5,000	ACT4	Airport Control Towers (S5L)
	5,000	ACT5	Airport Control Towers (PC1)
	5,000	ACT6	Airport Control Towers (C3L)
	5,000	ACT7	Airport Control Towers (W1)
	28,000	ARW1	Airport Runways
	8,000	ATB1	Airport Terminal Buildings (C2L)
	8,000	ATB2	Airport Terminal Buildings (S2L)
	8,000	ATB3	Airport Terminal Buildings (S1L)
	8,000	ATB4	Airport Terminal Buildings (S5L)
	8,000	ATB5	Airport Terminal Buildings (PC1)
	8,000	ATB6	Airport Terminal Buildings (C3L)
	8,000	ATB7	Airport Terminal Buildings (W1)
	1,400	APS1	Airport Parking Structures (C2L)
	1,400	APS2	Airport Parking Structures (S2L)
	1,400	APS3	Airport Parking Structures (S1L)
	1,400	APS4	Airport Parking Structures (S5L)
	1,400	APS5	Airport Parking Structures (PC1)
	1,400	APS65	Airport Parking Structures (C3L)
	5,000	AFF1	Airport Fuel Facility w/ Anchored Tanks, w/ BU Power
	5,000	AFF2	Airport Fuel Facility w/ Anchored Tanks, wo/ BU Power
	5,000	AFF3	Airport Fuel Facility w/ Unanchored Tanks, w/ BU Power
	5,000	AFF4	Airport Fuel Facility w/ Unanchored Tanks, wo/ BU Power
	5,000	AFF5	Airport Fuel Facility w/ Buried Tanks
	3,200	AMF1	Airport Maintenance & Hanger Facility
	8,000	ATBU1	Airport - General
	2,000	AFH1	Heliport
	500	AFO1	Seaport / Stolport / Gliderport / Seaplane

Table 15.17: Default Replacement Values of Utility System Components

System	Replacement Value (thous $)	Label	Component Classification
Potable Water	1	PWP1	Brittle Pipe (per break)
	1	PWP2	Ductile Pipe (per break)
	30,000	PWT1	Small WTP with Anchored Components < 50 MGD
	30,000	PWT2	Small WTP with Unanchored Components <50 MGD
	100,000	PWT3	Medium WTP with Anchored Components 50-200 MGD
	100,000	PWT4	Medium WTP with Unanchored Components 50-200 MGD
	360,000	PWT5	Large WTP with Anchored Components >200 MGD
	360,000	PWT6	Large WTP with Unanchored Components >200 MGD
	400	PWE1	Wells
	1,500	PST1	On Ground Anchored Concrete Tank
	1,500	PST2	On Ground Unanchored Concrete Tank
	800	PST3	On Ground Anchored Steel Tank
	800	PST4	On Ground Unanchored Steel Tank
	800	PST5	Above Ground Anchored Steel Tank
	800	PST6	Above Ground Unanchored Steel Tank
	30	PST7	On Ground Wood Tank
	150	PPP1	Small Pumping Plant with Anchored Equipment <10 MGD
	150	PPP2	Small Pumping Plant with Unanchored Equipment <10 MGD
	525	PPP3	Medium/Large Pumping Plant with Anchored Equipment >10 MGD
	525	PPP4	Med./Large Pumping Plant with Unanchored Equipment >10 MGD
Waste Water	1	WWP1	Brittle Pipe (per break)
	1	WWP2	Ductile Pipe (per break)
	60,000	WWT1	Small WWTP with Anchored Components <50 MGD
	60,000	WWT2	Small WWTP with Unanchored Components <50 MGD
	200,000	WWT3	Medium WWTP with Anchored Components 50-200 MGD
	200,000	WWT4	Medium WWTP with Unanchored Components 50-200 MGD
	720,000	WWT5	Large WWTP with Anchored Components >200 MGD
	720,000	WWT6	Large WWTP with Unanchored Components >200 MGD
	300	WLS1	Small Lift Stations with Anchored Components <10 MGD
	300	WLS2	Small Lift Stations with Unanchored Components <10 MGD
	1,050	WLS3	Medium/Large Lift Stations with Anchored Components >10 MGD
	1,050	WLS4	Med./Large Lift Stations with Unanchored Components >10 MGD
Oil	1	OIP1	Welded Steel Pipe with Gas Welded Joints (per break)
	1	OIP2	Welded Steel Pipe with Arc Welded Joints (per break)
	175,000	ORF1	Small Refinery with Anchored Equipment <100,000 bl/day
	175,000	ORF2	Small Refinery with Unanchored Equipment <100,000 bl/day
	750,000	ORF3	Medium/Large Refinery with Anchored Equipment >100,000 bl/day
	750,000	ORF4	Medium/Large Refinery with Unanchored Equipment >100,000 bl/day
	1,000	OPP1	Pumping Plant with Anchored Equipment
	1,000	OPP2	Pumping Plant with Unanchored Equipment
	2,000	OTF1	Tank Farms with Anchored Tanks
	2,000	OTF2	Tank Farms with Unanchored Tanks

Table 15.17: Default Replacement Values of Utility System Components (con't)

System	Replacement Value (thous $)	Label	Component Classification
Natural Gas	1	NGP1	Welded Steel Pipe with Gas Welded Joints (per break)
	1	NGP2	Welded Steel Pipe with Arc Welded Joints (per break)
	1,000	NGC1	Compressor Stations with Anchored Components
	1,000	NGC2	Compressor Stations with Unanchored Components
Electric Power Systems	10,000	ESS1	Low voltage (115 KV) substation, anchored comp.
	10,000	ESS2	Low voltage (115 KV) substation, unanchored comp.
	20,000	ESS3	Medium Voltage (230 KV) substation, anchored comp.
	20,000	ESS4	Medium Voltage (230 KV) substation, unanchored. comp.
	50,000	ESS5	High Voltage (500 KV) substation, anchored comp.
	50,000	ESS6	High Voltage (500 KV) substation, unanchored comp.
	3	EDC1	Distribution Circuits with seismically designed components
	3	EDC2	Distribution Circuits with standard components
	100,000	EPP1	Small Power Plants with Anchored Comp < 100 MW
	100,000	EPP2	Small Power Plants with Unanchored Comp <100 MW
	500,000	EPP3	Medium/Large Power Plants with Anchored Comp >100 MW
	500,000	EPP4	Medium/Large Power Plants with Unanchored Comp >100 MW
Commu-nication Systems	5,000	CCO1	Central Office with Anchored Components, w/BU Power
	5,000	CCO2	Central Office with Anchored Components, w/o BU Power
	5,000	CCO3	Central Office with Unanchored Components, w/BU Power
	5,000	CCO4	Central Office with Unanchored Components, w/o BU Power
	2,000	CBR1	Radio Broadcasting Station
	2,000	CBT1	TV Broadcasting Station
	2,000	CBW1	Weather Broadcasting Station
	2,000	CBO1	Other Communication Facility

15.3.1 Transportation Systems

This section describes the methodologies used to estimate direct economic losses related to transportation system damage. Transportation systems include highway, railway, light rail, bus, port, ferry, and airport systems. Damage models for each of these systems was discussed in detail in Chapter 7.

15.3.1.1 Highway Systems

In this subsection, damage ratios are presented for the following highway system components: roadways; bridges; tunnels. Damage ratios for bridges are expressed as a fraction of the component (bridge) replacement cost. Damage ratios for roadways are expressed as a fraction of the roadway replacement cost per unit length. Damage ratios for highway tunnels are expressed as a fraction of the liner replacement cost per unit length. The damage ratios for roadways, tunnels, and bridges are presented in Table 15.18.

Table 15.18: Damage Ratios for Highway System Components

Classification	Damage State	Best Estimate Damage Ratio	Range of Damage Ratios
Roadways	slight	0.05	0.01 to 0.15
	moderate	0.20	0.15 to 0.4
	extensive/ complete	0.70	0.4 to 1.0
Tunnel's Lining	slight	0.01	0.01 to 0.15
	moderate	0.30	0.15 to 0.4
	extensive	0.70	0.4 to 0.8
	complete	1.00	0.8 to 1.0
Bridges	slight	0.03	0.01 to 0.03
	moderate	0.08	0.02 to 0.15
	extensive	0.25	0.10 to 0.40
	complete	1.00*	0.30 to 1.00

* If the number of spans is greater than two, then the best estimate damage ratio for complete damage is [2/(number of spans)]

15.3.1.2 Railway Systems

In this subsection, damage ratios are presented for the following railway system components: tracks/roadbeds; bridges; tunnels; facilities. Damage ratios associated with bridges and facilities are expressed as a fraction of the component replacement cost. Damage ratios for tracks are expressed as a fraction of the replacement cost per length. Damage ratios for railway tunnels are expressed as a fraction of the liner replacement cost per unit length.

The damage ratios for railway bridges, fuel facilities, dispatch facilities, and urban stations and maintenance facilities, are presented in Table 15.19. The damage ratios for railway tracks and tunnels are the same as for urban roads and tunnels for the highway systems presented in Section 15.3.1.1. The damage ratios for bridges are computed in the same manner as for highway bridges. For a given damage state, the damage ratios for fuel and dispatch facilities are evaluated as the sum of the damage ratios of all the subcomponents multiplied by their respective percentages of the total component (fuel or dispatch facility) value. The subcomponents information is presented in Table 15D.1 of Appendix 15D.

Table 15.19: Damage Ratios for Railway System Components

Classification	Damage State	Best Estimate Damage Ratio	Range of Damage Ratios
Bridges	slight moderate extensive complete	0.12 0.19 0.40 1.00	0.01 to 0.15 0.15 to 0.4 0.4 to 0.8 0.8 to 1.0
Fuel Facilities	slight moderate extensive complete	0.15 0.39 0.80 1.00	0.01 to 0.15 0.15 to 0.4 0.4 to 0.8 0.8 to 1.0
Dispatch Facilities	slight moderate extensive complete	0.04 0.4 0.8 1.00	0.01 to 0.15 0.15 to 0.4 0.4 to 0.8 0.8 to 1.0
Urban Stations and Maintenance Facilities	slight moderate extensive complete	0.10 0.40 0.80 1.00	0.01 to 0.15 0.15 to 0.4 0.4 to 0.8 0.8 to 1.0

15.3.1.3 Light Rail Systems

In this subsection, damage ratios are presented for the following light rail system components: tracks/roadbeds; bridges; tunnels; facilities. Damage ratios for bridges and facilities are expressed as a fraction of the component replacement cost. Damage ratios for tracks are expressed as a fraction of the replacement value per unit length. Damage ratios for light rail tunnels are expressed as a fraction of the linear replacement cost.

The damage ratios for DC substations are presented in Table 15.20. The damage ratios for light rail tracks and tunnels are the same as for urban roads and tunnels for highway systems presented in Section 15.3.1.1. The damage ratios for dispatch facilities and bridges are the same as those for railway systems presented in Section 15.3.1.2. The damage ratios for the subcomponents of DC substations are estimated as the sum of the damage ratios of all the subcomponents multiplied by their respective percentages of the total substation value. The subcomponent information for the DC substations are presented in Table 15D.2 of Appendix 15D.

Table 15.20: Damage Ratios for DC Substations

Classification	Damage State	Best Estimate Damage Ratio	Range of Damage Ratios
DC Substations	slight moderate extensive complete	0.04 0.4 0.8 1.00	0.01 to 0.15 0.15 to 0.4 0.4 to 0.8 0.8 to 1.0

15.3.1.4 Bus Systems

In this subsection, damage ratios are presented for the following bus system components: urban stations; maintenance, fuel, and dispatch facilities. Damage ratios for these components are expressed as a fraction of the component replacement cost.

The damage ratios for bus system components are presented in Table 15.21. The damage ratios for urban stations and maintenance facilities are the same as those for railway systems presented in Section 15.3.1.2. The damage ratios for fuel and dispatch facilities are evaluated as the sum of the damage ratios of all the subcomponents multiplied by their respective percentages of the total component (fuel or dispatch facility) value. The subcomponent information is presented in Table 15D.3 of Appendix 15D.

Table 15.21: Damage Ratios for Bus System Components

Classification	Damage State	Best Estimate Damage Ratio	Range of Damage Ratios
Fuel Facilities	slight	0.15	0.01 to 0.15
	moderate	0.39	0.15 to 0.4
	extensive	0.8	0.4 to 0.8
	complete	1.00	0.8 to 1.0
Dispatch Facilities	slight	0.06	0.01 to 0.15
	moderate	0.4	0.15 to 0.4
	extensive	0.8	0.4 to 0.8
	complete	1.00	0.8 to 1.0

15.3.1.5 Port Systems

In this subsection, damage ratios are presented for the following port system components: waterfront structures (e.g., wharves, piers and sea-walls); cranes and cargo handling equipment; fuel facilities; warehouses. Damage ratios for these components are expressed as a fraction of the component replacement cost.

The damage ratios for port system components are presented in Table 15.22. The damage ratios for fuel facilities are evaluated as the sum of the damage ratios of all the subcomponents multiplied by their respective percentages of the total component (fuel facility) value. The subcomponent information is presented in Table 15D.4 of Appendix 15D.

Table 15.22: Damage Ratios for Port System Components

Classification	Damage State	Best Estimate Damage Ratio	Range of Damage Ratios
Waterfront Structures	slight moderate extensive complete	0.10 0.40 0.80 1.00	0.01 to 0.15 0.15 to 0.4 0.4 to 0.8 0.8 to 1.0
Cranes/Cargo Handling Equipment	slight moderate extensive/ complete	0.05 0.25 0.75	0.01 to 0.15 0.15 to 0.4 0.4 to 1.0
Warehouses	slight moderate extensive complete	0.10 0.40 0.80 1.00	0.01 to 0.15 0.15 to 0.4 0.4 to 0.8 0.8 to 1.0
Fuel Facilities	slight moderate extensive complete	0.16 0.39 0.8 1.00	0.01 to 0.15 0.15 to 0.4 0.4 to 0.8 0.8 to 1.0

15.3.1.6 Ferry Systems

In this subsection, damage ratios are presented for the following ferry system components: waterfront structures (e.g., wharf's piers and sea-walls); fuel, maintenance, and dispatch facilities; passenger terminals. Damage ratios for ferry system components are expressed as a fraction of the component replacement cost.

The damage ratios for ferry system components are presented in Table 15.23. The damage ratios for waterfront structures are the same as those for port systems. The damage ratios for maintenance and dispatch facilities are the same as those for railway systems. The damage ratios for passenger terminals are the same as those for urban stations in railway systems. The damage ratios for fuel facilities are evaluated as the sum of the damage ratios of all the subcomponents multiplied by their respective percentages of the total component (fuel facility) value. The subcomponent information is presented in Table 15D.4 of Appendix 15D.

Table 15.23: Damage Ratios for Ferry System Component

Classification	Damage State	Best Estimate Damage Ratio	Range of Damage Ratios
Fuel Facilities	slight moderate extensive complete	0.15 0.37 0.8 1.00	0.01 to 0.15 0.15 to 0.4 0.4 to 0.8 0.8 to 1.0

15.3.1.7 Airport Systems

In this subsection, damage ratios are presented for the following airport system components: runways; control towers; fuel facilities; terminal buildings; maintenance and hangar facilities; parking structures. Damage ratios for the airport system components are expressed as a fraction of the component replacement cost.

The damage ratios for airport system components are presented in Table 15.24. The damage ratios for fuel facilities are evaluated as the sum of the damage ratios of all the subcomponents multiplied by their respective percentages of the total component (fuel facility) value. The subcomponent information is presented in Table 15D.4 of Appendix 15D.

Table 15.24: Damage Ratios for Airport System Components

Classification	Damage State	Best Estimate Damage Ratio	Range of Damage Ratios
Runways	slight	0.05	0.01 to 0.4
	moderate	0.05	0.01 to 0.4
	extensive	0.8	0.4 to 0.8
	complete	1.0	0.8 to 1.0
Control Towers	slight	0.10	0.01 to 0.15
	moderate	0.40	0.15 to 0.4
	extensive	0.80	0.4 to 0.8
	complete	1.00	0.8 to 1.0
Terminal Buildings	slight	0.10	0.01 to 0.15
	moderate	0.40	0.15 to 0.4
	extensive	0.80	0.4 to 0.8
	complete	1.00	0.8 to 1.0

Table 15.24: Damage Ratios for Airport System Components (Continued)

Classification	Damage State	Best Estimate Damage Ratio	Range of Damage Ratios
Parking Structures	slight moderate extensive complete	0.10 0.40 0.80 1.00	0.01 to 0.15 0.15 to 0.4 0.4 to 0.8 0.8 to 1.0
Fuel Facilities	slight moderate extensive complete	0.14 0.37 0.8 1.00	0.01 to 0.15 0.15 to 0.4 0.4 to 0.8 0.8 to 1.0
Maintenance & Hangar Facilities	slight moderate extensive complete	0.10 0.40 0.80 1.00	0.01 to 0.15 0.15 to 0.4 0.4 to 0.8 0.8 to 1.0

15.3.2 Utility Systems

This section describes the methodologies used to estimate direct economic losses related to utility system damage. Utility systems include potable water, waste water, oil, natural gas, electric power, and communication systems. The estimation of the direct economic losses associated with each of these systems is presented in the following sections.

15.3.2.1 Potable Water Systems

In this subsection, damage ratios are presented for the following potable water system components: pipelines; water treatment plants; wells; storage tanks; pumping plants. Damage ratios for these components are expressed as a fraction of the component replacement cost.

The damage ratios for potable water system components are presented in Table 15.25. The damage ratios for water treatment plants, wells, and pumping plants are evaluated as the sum of the damage ratios of all the subcomponents multiplied by their respective percentages of the total component value. The subcomponent information is presented in Table 15D.5 of Appendix 15D.

Table 15.25: Damage Ratios for Potable Water Systems

Classification	Damage State	Best Estimate Damage Ratio	Range of Damage Ratios
Pipelines	leak break	0.10* 0.75*	0.05 to 0.20 0.5 to 1.0
Water Treatment Plants	slight moderate extensive complete	0.08 0.4 0.77 1.00	0.01 to 0.15 0.15 to 0.4 0.4 to 0.8 0.8 to 1.0
Tanks	slight moderate extensive complete	0.20 0.40 0.8 1.00	0.01 to 0.15 0.15 to 0.4 0.4 to 0.8 0.8 to 1.0
Wells and Pumping Plants	slight moderate extensive complete	0.05 0.38 0.8 1.00	0.01 to 0.15 0.15 to 0.4 0.4 to 0.8 0.8 to 1.0

* % of the replacement cost for one 20 ft. pipe segment

15.3.2.2 Waste Water Systems

In this subsection, damage ratios are presented for the following waste water system components: underground sewers and interceptors; waste water treatment plants; lift stations. Damage ratios for these components are expressed as a fraction of the component replacement cost.

The damage ratios for waste water system components are presented in Table 15.26. The damage ratios for lift stations are same as those for pumping plants in potable water systems presented in Section 15.3.2.2. The damage ratios for waste water treatment plants are evaluated as the sum of the damage ratios of all the subcomponents multiplied by their respective percentages of the total component value. The subcomponent information is presented in Table 15D.6 of Appendix 15D.

Table 15.26: Damage Ratios for Waste Water Systems

Classification	Damage State	Best Estimate Damage Ratio	Range of Damage Ratios
Underground Sewers & Interceptors	leak break	0.10 0.75	0.05 to 0.20 0.5 to 1.0
Waste Water Treatment Plants	slight moderate extensive complete	0.10 0.37 0.65 1.00	0.01 to 0.15 0.15 to 0.4 0.4 to 0.8 0.8 to 1.0

15.3.2.3 Oil Systems

In this subsection, damage ratios are presented for the following oil system components: buried pipes; refineries; pumping plants; tank farms. Damage ratios for these components are expressed as a function of the component replacement cost.

The damage ratios for oil system components are presented in Table 15.27. The damage ratios for refineries, pumping plants, and tank farms are evaluated as the sum of the damage ratios of all the subcomponents multiplied by their respective percentages of the total component value. The subcomponent information is presented in Table 15D.7 of Appendix 15D.

Table 15.27: Damage Ratios for Oil Systems

Classification	Damage State	Best Estimate Damage Ratio	Range of Damage Ratios
Buried Pipes	leak break	0.10 0.75	0.05 to 0.20 0.5 to 1.0
Refineries	slight moderate extensive complete	0.09 0.23 0.78 1.00	0.01 to 0.15 0.15 to 0.4 0.4 to 0.8 0.8 to 1.0
Pumping Plants	slight moderate extensive complete	0.08 0.4 0.8 1.00	0.01 to 0.15 0.15 to 0.4 0.4 to 0.8 0.8 to 1.0
Tank Farms	slight moderate extensive complete	0.13 0.4 0.8 1.00	0.01 to 0.15 0.15 to 0.4 0.4 to 0.8 0.8 to 1.0

15.3.2.4 Natural Gas Systems

In this subsection, damage ratios are presented for the following gas system components: buried pipes; compressor stations. Damage ratios for these components are expressed as a fraction of the component replacement cost. The damage ratios for buried pipes are the same as those for oil systems. The damage ratios for compressor stations are the same as those for pumping plants in the oil system.

15.3.2.5 Electric Power Systems

In this subsection, damage ratios are presented for the following electric power system components: substations; distribution circuits; generation plants. Damage ratios for these components are expressed as a fraction of the component replacement cost.

The damage ratios for electric power system components are presented in Table 15.28. The damage ratios for substations and generation plants are evaluated as the sum of the damage ratios of all the subcomponents multiplied by their respective percentages of the total component value. The subcomponent information is presented in Table 15D.8 & 15D.9 of Appendix 15D.

Table 15.28: Damage Ratios for Electric Power Systems

Classification	Damage State	Best Estimate Damage Ratio	Range of Damage Ratios
Substations	slight moderate extensive complete	0.05 0.11 0.55 1.00	0.01 to 0.15 0.15 to 0.4 0.4 to 0.8 0.8 to 1.0
Distribution Circuits	slight moderate extensive complete	0.05 0.15 0.60 1.00	0.01 to 0.15 0.15 to 0.4 0.4 to 0.8 0.8 to 1.0
Generation Plants	slight moderate extensive complete	0.08 0.35 0.72 1.00	0.01 to 0.15 0.15 to 0.4 0.4 to 0.8 0.8 to 1.0

15.3.2.6 Communication Systems

In this subsection, damage ratios are presented for communication system central offices. Damage ratios for central offices are expressed as a fraction of the central office replacement cost.

The damage ratios for central offices are presented in Table 15.29. The damage ratios for a central office are evaluated as the sum of the damage ratios of all the subcomponents multiplied by their respective percentages of the total component (central office) value. The subcomponent information is presented in Table 15D.10 of Appendix 15D.

Table 15.29: Damage Ratios for Communication System Component

Classification	Damage State	Best Estimate Damage Ratio	Range of Damage Ratios
Central Office	slight	0.09	0.01 to 0.15
	moderate	0.35	0.15 to 0.4
	extensive	0.73	0.4 to 0.8
	complete	1.00	0.8 to 1.0

15.4. **References**

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Appendix 15A
Relationship Between Building Damage and Business Interruption

The subject of business and service interruption due to building damage has been identified for some time as an important contributor to indirect economic losses following earthquakes.

The issue of relating building damage to business interruption, and developing some statistical measures has been little researched, and available information is largely anecdotal. ATC-13 provided extensive coverage of the topic of building repair and loss of function, at the same time noting that:

" ... it is clear that there is a great variation in repair and demolition actions taken in connection with buildings that are moderately or severely damaged. There is also great variation for the loss of function associated with a given degree of damage.... The paucity of data currently available precludes describing loss of function based on statistical data from past events."

ATC-13 provided detailed tables with estimates of loss of function times for all the ATC-13 social classes of buildings (and all lifelines). These tables, which were developed by expert opinion, provided estimates of the time to restore 30%, 60%, and 100% of useability, for each of the six ATC-13 damage states.

Since ATC-13 was published, the information that relates building damage to loss of function continues to be unsystematic and anecdotal. A study of damage and loss of function for 14 industrial and administrative buildings in the Loma Prieta earthquake shows a typical wide spread of conditions and consequences (Phipps, et. al, 1992). Table 15A-1 summarizes some of the information from this study. It is possible that surveys of the recovery after the Northridge earthquake may provide some more systematic information on this issue.

**Table 15A.1: Summary of Building Damage Vs Restoration Time:
for 14 Industrial/Administrative Low-Rise Buildings, Loma Prieta Earthquake
(Time in Days) (from Phipps, et. al., 1992)**

#	Structure Type	Damage Percentage	Restoration Time (days)	Description of Damage
1	Tilt-up	2	5	roof-wall connections
2.	Steel	20	180	window wall cracked
3	Steel	2	1	piping, clogs
4	Steel	37	270	floor cracked
5	Steel	33	270	bracing buckled
6	Steel	32	270	bracing buckled
7	Steel	33	270	bracing buckled
8	Steel	NA	360	sprinklers
9	Steel	23	150	buckled bracing
10	Tilt-up	89	540	cracked walls
11	Tilt-up	60	90	failed roof
12	Precast	NA	90	wall-floor connections
13	Steel	42	180	asbestos
14	Steel	NA	21	radioactive contamination

Surveys of available information and experience suggest that the ATC-13 attempt to use expert opinion resulted in more apparent precision in estimating than was justified by the data. In addition, the attempt to provide 30%, 60% and 100% restoration estimates may be relevant for lifelines, but has little meaning for building function. Typical business and service facilities either provide something approaching 100% function in a fairly short time after the earthquake or cease to exist. Considerable improvisation and ingenuity is usually applied by management and staff to ensure rapid restoration .

Thus, this methodology presents a much simplified set of estimates, which it is felt match the current state of knowledge. In doing this, the distinction between the time needed for repair and the often much longer time needed for the whole repair project is recognized by multipliers applied to the extended construction time. In addition, the fact that business function can be to a large extent divorced from the building that housed it is also recognized by these multipliers. The latter situation might vary greatly among different kinds of business and users of the methodology may find it useful to discuss with key businesses in their area the functional consequences of building damage. It is also a reasonable supposition that businesses that have not experienced earthquake damage tend to overestimate its effect on their operation because it is hard for them to imagine emergency improvisation since they lack the experience.

Table 15A-2 shows a correlation between the the methodology's damage states and the ATC-13 estimates for functional restoration time: these may be compared with the estimates in Tables 15.09, 15.10 and 15.11 The ATC estimates assume that repair time is equivalent to restoration time.

Table 15A.2: ATC-13: Restoration Times Related to Occupancy Classes (Time in days) (ATC-13, 1985)

No.	Label	Occupancy Class	Damage State		
			Slight	**Moderate**	**Extensive**
		Residential			
1	RES1	Single Family Dwelling	3	11-72	72-146
2	RES2	Mobile Home	3	11-72	72-146
3-8	RES3a-f	Multi Family Dwelling	3	11-72	72-146
9	RES4	Temporary Lodging	3	11-72	72-146
10	RES5	Institutional Dormitory	3	11-72	72-146
11	RES6	Nursing Home	3	11-72	72-146
		Commercial			
12	COM1	Retail Trade	20	71-202	202-347
13	COM2	Wholesale Trade	20	71-202	202-347
14	COM3	Personal and Repair Services	20	71-202	202-347
15	COM4	Professional/Technical Services	20	71-202	202-347
16	COM5	Banks/Financial Institutions	20	71-202	202-347
17	COM6	Hospital	56	156-338	338-613
18	COM7	Medical Office/Clinic	56	156-338	338-613
19	COM8	Entertainment & Recreation	20	71-202	202-343
20	COM9	Theaters	20	71-202	202-343
21	COM10	Parking	6	24-76	76-172
		Industrial			
22	IND1	Heavy	23	99-240	240-405
23	IND2	Light	23	99-240	240-405
24	IND3	Food/Drugs/Chemicals	16	72-235	235-380
25	IND4	Metals/Minerals Processing	22	99-248	248-405
26	IND5	High Technology	16	112-258	258-429
27	IND6	Construction	28	68-121	121-257
		Agriculture			
28	AGR1	Agriculture	9	26-77	77-154
		Religion/Non-Profit			
29	REL1	Church/Membership Organization	17	72-215	215-382
		Government			
30	GOV1	General Services	28	91-196	196-396
31	GOV2	Emergency Response	18	60-134	134-256
		Education			
32	EDU1	Schools/Libraries	16	72-183	183-362
33	EDU2	Colleges/Universities	16	72-183	183-362

Note: Methodology Damage State
Slight = ATC #3: (CDF 5%)
Moderate: 30%, = between ATC 4-5 (20 - 45%)
Extensive 50%, = between ATC 5-6 (45 - 80%)

APPENDIX 15B. Lifeline Subcomponent Information (Damage Ratios & Fraction of Value)

Table15B.1. Subcomponents for the Railway System(G&E, 1994)

Sub-Component	Fraction of Total Component Value	Damage State	Damage Ratio
Fuel Facilities			
Electric Backup Power	2 %	slight moderate	0.20 0.70
Tanks	86 %	slight moderate extensive complete	0.20 0.40 0.85 1.00
Pump Building	2 %	slight moderate extensive complete	0.10 0.40 0.80 1.00
Horizontal Pumps	5 %	extensive	0.75
Electrical Equipment	5 %	moderate	0.50
Dispatch Facilities			
Electric Backup Power	30 %	slight moderate	0.20 0.70
Building	20 %	slight moderate extensive complete	0.10 0.40 0.80 1.00
Electrical Equipment	20 %	moderate	0.80
Railway Bridges			
Column		slight extensive complete	0.05 0.25 0.8
Abutment		slight moderate extensive	0.02 0.075 0.15
Connection		moderate extensive	0.01 0.02
Deck		slight	0.05

Table15B.2. Subcomponents for DC Substations (G&E, 1994)

Subcomponent	Fraction of Total Component Value	Damage State	Damage Ratio
Building	35 %	slight moderate extensive complete	0.10 0.40 0.80 1.00
Equipment	65 %	moderate	0.80

Table15B.3. Subcomponents for the Bus System (G&E, 1994)

Subcomponent	Fraction of Total Component Value	Damage State	Damage Ratio
Fuel Facilities			
Electric Backup Power	2 %	slight moderate	0.20 0.70
Tanks	79 %	slight moderate extensive complete	0.20 0.40 0.85 1.00
Building	11 %	slight moderate extensive complete	0.10 0.40 0.80 1.00
Pumps	4 %	extensive	0.75
Electrical Equipment	4 %	moderate	0.50
Dispatch Facilities			
Electric Backup Power	15 %	slight moderate	0.20 0.70
Building	30 %	slight moderate extensive complete	0.10 0.40 0.80 1.00
Electrical Equipment	55 %	moderate	0.80

Table15B.4. Subcomponents for Port, Ferry and Airport Systems (G&E, 1994)

Sub-Component	Fraction of Total Component Value	Damage State	Damage Ratio
Port Fuel Facilities			
Electric Backup Power	5 %	slight moderate	0.20 0.70
Tanks	70 %	slight moderate extensive complete	0.20 0.40 0.85 1.00
Pump Building	5 %	slight moderate extensive complete	0.10 0.40 0.80 1.00
Horizontal Pumps	10 %	extensive	0.75
Electrical Equipment	10 %	moderate	0.50
Ferry Fuel Facilities			
Electric Backup Power	3 %	slight moderate	0.20 0.70
Tanks	72 %	slight moderate extensive complete	0.20 0.40 0.85 1.00
Pump Building	5 %	slight moderate extensive complete	0.10 0.40 0.80 1.00
Horizontal Pumps	10 %	extensive	0.75
Electrical Equipment	10 %	moderate	0.50
Airport Fuel Facilities			
Electric Backup Power	6 %	slight moderate	0.20 0.70
Tanks	64 %	slight moderate extensive complete	0.20 0.40 0.85 1.00
Pump Building	6 %	slight moderate extensive complete	0.10 0.40 0.80 1.00
Horizontal Pumps	12 %	extensive	0.75
Electrical Equipment	12 %	moderate	0.50

Table15B.5. Subcomponent for Potable Water System Components (G&E, 1994)

Sub-Component	Fraction of Total Component Value	Damage State	Damage Ratio
Water Treatment Plant			
Electric Backup Power	4 %	slight moderate	0.20 0.70
Chlorination Equipment	4 %	slight moderate	0.15 0.50
Sediment Flocculation	12 %	slight moderate	0.20 0.50
Chemical Tanks	20 %	slight moderate	0.20 0.75
Electric Equipment	30 %	moderate	0.60
Elevated Pipe	10 %	extensive complete	0.65 0.90
Filter Gallery	20 %	complete	1.00
Wells			
Electric Backup Power	16 %	slight moderate	0.20 0.70
Well Pump	34 %	extensive	0.75
Building	16 %	slight moderate extensive complete	0.10 0.40 0.80 1.00
Electric Equipment	34 %	moderate	0.60
Pumping Plants			
Electric Backup Power	16 %	slight moderate	0.20 0.70
Pumps	34 %	extensive	0.75
Building	16 %	slight moderate extensive complete	0.10 0.40 0.80 1.00
Electrical Equipment	34 %	moderate	0.60

Table15B.6. Subcomponets for Waste Water Treatment (G&E, 1994)

Subcomponents	Fraction of Total Component Value	Damage State	Damage Ratio
Electric Backup Power	5 %	slight moderate	0.20 0.70
Chlorination Equipment	3 %	slight moderate	0.15 0.50
Sediment Flocculation	36 %	slight moderate extensive	0.20 0.50 0.80
Chemical Tanks	7 %	slight moderate	0.20 0.75
Electrical/ Mechanical Equipment	14 %	moderate	0.60
Elevated Pipe	8 %	extensive complete	0.65 0.90
Buildings	27 %	complete	1.00

Table15B.7 Subcomponents for Crude & Refined Oil Systems(G&E, 1994)

Sub-Component	Fraction of Total Component Value	Damage State	Damage Ratio
Refineries			
Electric Backup Power	3 %	slight moderate	0.20 0.70
Electrical/ Mechanical Equipment	6 %	moderate	0.60
Tanks	42 %	slight moderate extensive complete	0.20 0.40 0.85 1.00
Stacks	42 %	extensive	0.80
Elevated Pipe	7 %	complete	1.00
Pumping Plants			
Electric Backup Power	30 %	slight moderate	0.20 0.70
Pump	20 %	extensive	0.75
Building	20 %	slight moderate extensive complete	0.10 0.40 0.80 1.00
Electrical/ Mechanical Equipment	30 %	moderate	0.60
Tank Farms			
Electric Backup Power	6 %	slight moderate	0.20 0.70
Electrical/ Mechanical Equipment	24 %	moderate	0.60
Tanks	58 %	slight moderate extensive complete	0.20 0.40 0.85 1.00
Elevated Pipes	12 %	extensive complete	0.65 0.90

Table15B.8. Subcomponents for Electrical Substations (G&E, 1994)

Classification	Fraction of Total Component Value	Damage State	Damage Ratio
Transformers	68 %	extensive complete	0.50 1.00
Circuit Breakers	26 %	slight moderate extensive complete	0.17 0.33 0.67 1.00
Disconnect Switches	3 %	slight moderate extensive complete	0.17 0.42 0.67 1.00
Current Transformers	3 %	extensive complete	0.67 1.00

Table15B.9. Subcomponents for Generation Plant (G&E, 1994)

Subcomponents	Fraction of Total Component Value	Damage State	Damage Ratio
Electrical Equipment	17 %	slight moderate	0.30 0.60
Boilers & Pressure Vessels	19 %	moderate	0.50
Vertical vessels	5 %	moderate extensive	0.50 0.80
Pumps	9 %	extensive	0.75
Horizontal vessels	14 %	complete	1.00
Large motor operated valves	5 %	complete	1.00
Boiler Building	17 %	slight moderate extensive complete	0.10 0.40 0.80 1.00
Turbine Building	14 %	slight moderate extensive complete	0.10 0.40 0.80 1.00

Table15B.10. Subcomponents for Communication Centers (G&E, 1994)

Subcomponents	Fraction of Total Component Value	Damage State	Damage Ratio
Electric Power (Backup)	15 %	slight moderate	0.20 0.70
Switching Equipment	49 %	slight moderate extensive complete	0.05 0.20 0.60 1.00
Building	36 %	slight moderate extensive complete	0.10 0.40 0.80 1.00

Chapter 16
Indirect Economic Losses

16.1 Introduction

This Chapter is written with several goals in mind. First, it is intended to familiarize the reader with the concept of indirect loss, including a brief discussion of input-output models, the traditional approach for tracing interindustry ripple effects (Sections 16.2 and 16.3).

Second, an algorithm for addressing supply shocks (the engine of the Indirect Loss Module) is developed and explained. Section 16.4 develops a method for computing indirect losses, one that addresses the effects of supply and demand disruptions. The Indirect Loss Module is a computational algorithm which accounts for earthquake induced supply shortages (forward linkages) and demand reductions (backward linkages). The module is a version of a computable general equilibrium model designed to rebalance a region's interindustry trade flows based on discrepancies between sector supplies and demands. The flowchart of the overall methodology, highlighting the Indirect Loss Module and its relationship to other modules is shown in Figure 16.1.

Third, the chapter discusses data requirements and operational issues related to running the module for different levels of analysis. Section 16.5 provides an overview of input data, module operation, and results output in a Default or User-Supplied Data Analysis. It also includes suggestions for approaches to conducting a Advanced analysis.

Finally, a number of experiments are reported to assist the user in interpreting the Module’s results. Section 16.6 analyzes how patterns of direct damage, preexisting economic conditions (unemployment, import-export options, and economic structure) and external assistance alter indirect loss. Example solutions based on the Northridge earthquake are provided, along with the results of Monte Carlo simulations. The former is provided to illustrate how the model can be applied, the latter to suggest the wide range of possible outcomes. Lastly, a set of helpful observations are presented.

16.2 What are Indirect Losses?

Earthquakes may produce dislocations in economic sectors not sustaining direct damage. All businesses are forward-linked (rely on regional customers to purchase their output) or backward-linked (rely on regional suppliers to provide their inputs) and are thus potentially vulnerable to interruptions in their operation. Such interruptions are called indirect economic losses. Note that these losses are not confined to immediate customers or suppliers of damaged enterprises. All of the successive rounds of customers of customers and suppliers of suppliers are impacted. In this way, even limited earthquake physical damage causes a chain reaction, or ripple effect, that is transmitted throughout the regional economy.

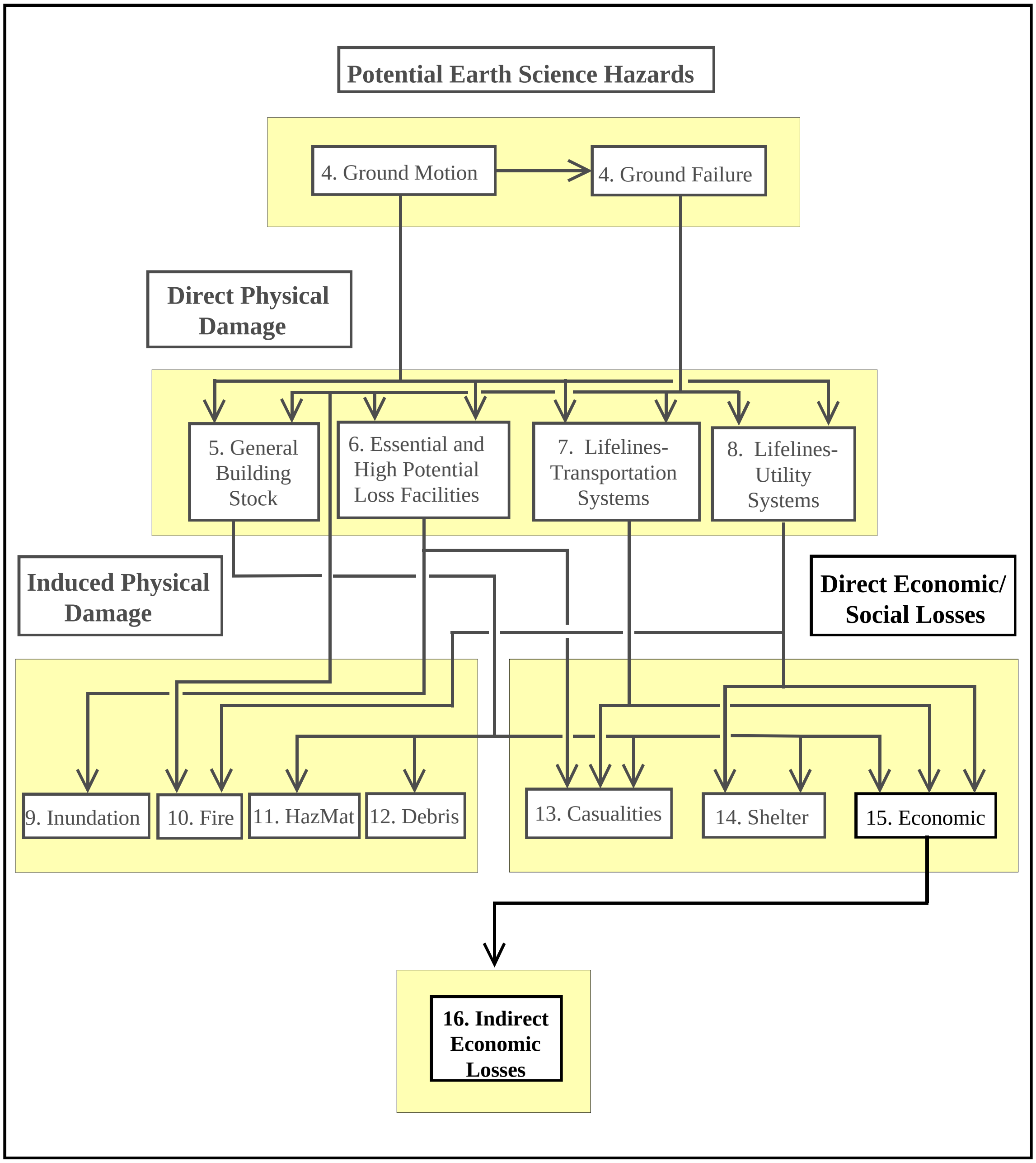

Figure 16.1 Indirect Loss Estimation Relationship to Other Modules in the Earthquake Loss Estimation Methodology

The extent of indirect losses depends upon such factors as the availability of alternative sources of supply and markets for products, the length of the production disturbance, and deferability of production. Figure 16.2 provides a highly-simplified depiction of how direct damages induce indirect losses. In this economy firm A ships its output to one of the factories that produce B, and that factory ships to C. Firm C supplies households with a final product (an example of a final demand, FD) and could also be a supplier of intermediate input demand to A and B. There are two factories producing output B, one of which is destroyed in the earthquake. The first round of indirect losses occurs because: 1) direct damage to production facilities and to inventories cause shortages of inputs for firms needing these supplies (forward-linked indirect loss); 2) damaged production facilities reduce their demand for inputs from other producers (backward-linked indirect loss); or 3) reduced availability of goods and services stunt household, government, investment, and export demands (all part of final demand).

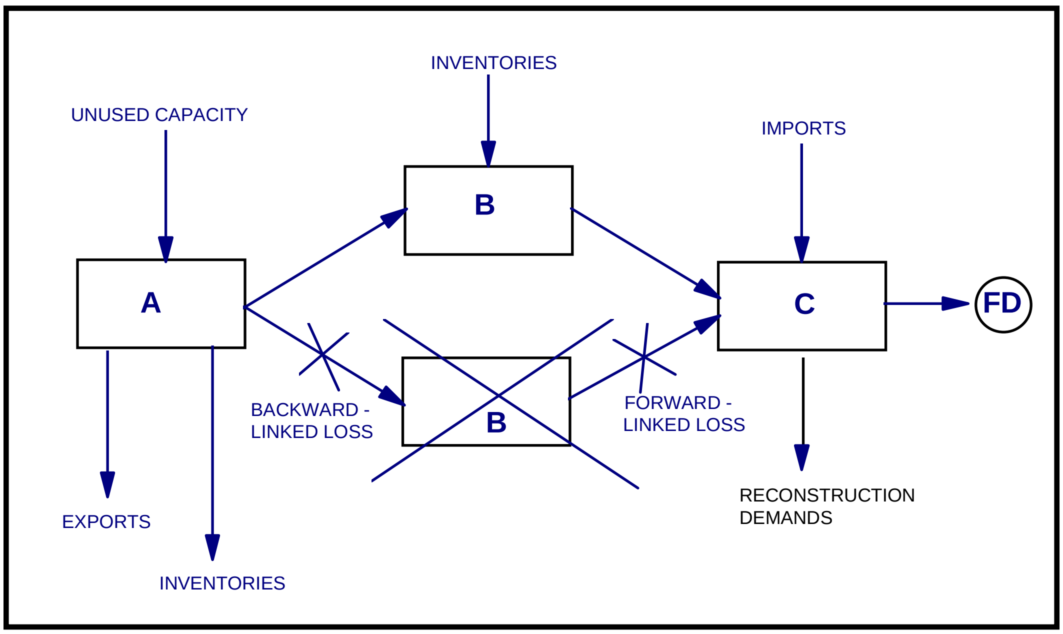

Figure 16.2 Indirect Losses and Adjustments to Lessen Them

16.2.1 Supply Shortages and Forward Linked Losses

The supply shortages caused as a result of reduced availability of input B could cripple factory C, if C is unable to locate alternative sources. Three options are possible: 1) secure additional supplies from outside the region (imports); 2) obtain additional supplies from the undamaged factory (excess capacity); and 3) draw from B's unsold stock of output (inventories). The net effect of diminished supplies are referred to as forward-linked losses, the term forward (often referred to as downstream) implying that the impact of direct damages is shifted to the next stage or stages of the production process.

16.2.2 Demand Effects and Backward Linked Losses

Disasters can also produce indirect losses if producer and consumer demands for goods and services are reduced. If, in the example provided in Figure 16.2, firm B has a reduced demand for inputs from A, then A may be forced to scale back operations. As in the case of forward-linked losses, the affected firms may be able to circumvent a weakened market, in this case by either finding alternative outlets such as exports or building up inventory.[1]

The higher rate of unemployment caused by direct damages and subsequent indirect factory slowdowns or closures would reduce personal income payments and could cause normal household demands to erode. However, it is more likely that the receipt of disaster assistance, unemployment compensation, or borrowing, would buoy household spending throughout the reconstruction period. Evidence from recent events (Hurricanes Andrew and Hugo, the Loma Prieta Earthquake and the Northridge Earthquake) confirms that normal household demands are only slightly altered by disaster in the short-run. As a result of this observation, the Indirect Loss Module discussed below delinks household incomes and demands.

16.2.3 Regional vs. National Losses

It has sometimes appeared that natural disasters tend to stimulate employment and revitalize a region. Clearly, the generous federal disaster relief policies in place after the 1964 Alaskan earthquake, the 1971 San Fernando earthquake, and Hurricane Agnes in 1972, served to buoy the affected economies, thereby preventing the measurement of significant indirect losses. From a regional accounting stance, it appeared that the net losses were inconsequential. However, this viewpoint fails to take into account the cost of disasters on both household and federal budgets.

Some, if not most, public and private post-disaster spending is unfunded; that is, it is not paid for out of current tax revenues and incomes. In the case of households this amounts to additional indebtedness which shifts the burden or repayment to some future time period. Federal expenditures are not budget neutral either. As in the case of households, governments cannot escape the financial implications of increased spending for disaster relief. Either lower priority programs must be cut, taxes raised, or the federal debt increased. The first two options simply shift the reduction in demand and associated indirect damages to other regions. Projects elsewhere may be canceled, services curtailed, and/or household spending diminished as after-tax incomes shrink. The debt option provides no escape either, since it, too, places the burden on others, e.g., a future generation of taxpayers.

From a national accounting stance, indirect losses can be measured by deriving regional indirect impacts, adjusted for the liability the Federal government incurs in providing disaster relief, and for offsetting increases in outputs elsewhere. The positive effects

[1]Building up inventory is not a permanent solution, since eventually the inventories have to be sold. Firms may be willing to do so on a temporary basis, hoping that market conditions will improve at a later date.

outside aid produces for the region are to some degree offset by negative effects produced by the three federal budget options. Since it is impossible to know *a priori* which option the federal government will utilize, it is safest to assume that the two effects cancel, i.e., that the positive outcomes from federal aid are offset by the negative national consequences caused by the budget shortfall.

Since the primary user of the Loss Estimation Methodology is likely to be the local entity involved in seismic design and zoning decisions, the Indirect Loss Module is designed accordingly. That is, it adopts a local accounting stance. One simplistic approach to obtaining a national measure of net loss would be to exercise the Loss Module excluding outside federal assistance.

16.3 Interindustry Models

Input-output techniques are widely utilized to assess the total (direct plus higher-order) economic gains and losses caused by sudden changes in the demand for a region's products. Higher demand for rebuilding and a lower demand for tourism, for example, lend themselves to traditional input-output I-O methods. This technique is relatively simple to apply and is already in widespread use in state and local agencies, though not necessarily those associated with emergency management. However, input-output models compromise realism, primarily in the area of supply bottlenecks. Although the Indirect Loss Module addresses both supply and demand shocks in a more sophisticated manner, it is based on the same foundation as the input-output model—a region's interindustry input requirements. Because the two approaches share a common base, we begin by introducing the principles underlying input-output analysis, with an emphasis on demand disturbances, and then extend the framework to accommodate supply shocks.

Input-output analysis was first formulated by Nobel laureate Wassily Leontief and has gone through several decades of refinement by Leontief and many other economists. At its core is a static, linear model of all purchases and sales between sectors of an economy, based on the technological relationships of production. Input-output (I-O) modeling traces the flows of goods and services among industries and from industries to household, governments, investment, and exports. These trade flows indicate how much of each industry's output is comprised of its regional suppliers' products, as well as inputs of labor, capital, imported goods, and the services of government. The resultant matrix can be manipulated in several ways to reveal the economy's interconnectedness, not only in the obvious manner of direct transactions but also in terms of dependencies several steps removed (e.g., the construction of a bridge generates not only a direct demand for steel but also indirect demands via steel used in machines for its fabrication and in railroad cars for its transportation).

The very nature of this technique lays it open to several criticisms: the models are insensitive to price changes, technological improvements, and the potential for input substitution at any given point in time. However, even with these limitations, I-O techniques are a valuable guide for the measurement of some indirect losses. A very brief technical review is provided for those readers who may be unfamiliar with interindustry modeling.[2]

16.3.1 A Primer on Input-Output Techniques

The presentation is restricted to a simple three industry economy. The shipments depicted as arrows in Figure 16.2 are represented as annual flows in Table 16.1. The *X*'s represent the dollar value of the good or service shipped from the industry listed in the left-hand heading to the industry listed in the top heading. The *Y*'s are shipments to consumers (goods and services), businesses (investment in plant and equipment and retained inventories), government (goods, services and equipment), to other regions (exported goods and services). The *V*'s are the values-added in each sector, representing payments to labor (wages and salaries), capital (dividends, rents, and interest), natural resources (royalties and farm rents), and government (indirect business taxes). The *M*'s represent imports to each producing sector from other regions.

A basic accounting balance holds: total output of any good is sold as an intermediate input to all sectors and as final goods and services:

$$X_A = X_{AA} + X_{AB} + X_{AC} + Y_A \tag{16-1}$$

Rearranging terms, the amount of output available from any industry for final demand is simply the amount produced less the amount shipped to other industries.

[2] Input-output and "interindustry" are often used synonymously because of the emphasis in I-O on the sectoral unit of analysis, mainly comprised of producing industries. Strictly speaking, however, interindustry refers to a broad set of modeling approaches that focus on industry interactions, including activity analysis, linear programming, social accounting matrices, and even computable general equilibrium models. Most of these have an input-output table at their core. The reader interested in a more complete understanding of I-O analysis is referred to Rose and Miernyk (1989) for a brief survey; Miller and Blair (1985) for an extensive textbook treatment; and Boisvert (1992) for a discussion of its application to earthquake impacts. For other types of interindustry models applied to earthquake impact analysis, the reader is referred to the work of Rose and Benavides (1997) for a discussion of mathematical programming and to Brookshire and McKee (1992) for a discussion of computable general equilibrium analysis.

Table 16.1 Intersectoral Flows of a Hypothetical Regional Economy (dollars)

To From	A	B	C	Final Demand	Gross Output
A	X_{AA}	X_{AB}	X_{AC}	Y_A	X_A
B	X_{BA}	X_{BB}	X_{BC}	Y_B	X_B
C	X_{CA}	X_{CB}	X_{CC}	Y_C	X_C
V	V_A	V_B	V_C		
M	M_A	M_B	M_C		
Gross Outlay	X_A	X_B	X_C	Y	X

To transform the I-O accounts into an analytical model, it is then assumed that the purchases by each of the industries have some regularity and thus represent technological requirements. Technical coefficients that comprise the structural I-O matrix are derived by dividing each input value by its corresponding total output. That is:

$$a_{AA} = \frac{X_{AA}}{X_A}; \qquad a_{AB} = \frac{X_{AB}}{X_B}; \qquad a_{AC} = \frac{X_{AC}}{X_C}; \tag{16-2}$$

The a's are simply the ratios of inputs to outputs. An a_{AB} of 0.2 means that 20 percent of industry B's total output is comprised of product A.

Equation (16-1) can then be written as:

$$X_A = a_{AA} X_A + a_{AB} X_B + a_{AC} X_C + Y_A \tag{16-3}$$

In matrix form Equation (16-3) is:

$$X = AX + Y \tag{16-4}$$

To solve for the gross output of each sector, given a set of final demand requirements, we proceed through the following steps:

$$(I - A)X = Y \tag{16-5}$$

$$(I - A)^{-1}Y = X \tag{16-6}$$

The term $(I - A)^{--1}$ is known as the Leontief Inverse. It indicates how much each sector's output must increase as a result of (direct and indirect) demands to deliver an additional unit of final goods and services of each type. It might seem that a $1 increase in the final demand for product A would result in the production of just an additional $1 worth of A. However, this ignores the interdependent nature of the industries. The production of A requires ingredients from a combination of industries, A, B, and/or C. Production of B, requires output from A, B, and/or C, and so on. Thus, the one dollar increase in demand for A will stimulate A's production to change by more than one dollar. The result is a multiple of the original stimulus, hence, the term "multiplier effect" (a technical synonym for ripple effect).

Given the assumed regularity in each industry's production requirements, the Leontief Inverse need only be computed once for any region (at a given point in time) and can then be used for various policy simulations reflected in changes in final demand (e.g., the impact of public sector investment) as follows:

$$(I - A)^{-1} \Delta Y = \Delta X \qquad (16\text{-}7)$$

More simply, the column sums of the Leontief Inverse are sectoral multipliers, M, specifying the total gross output of the economy directly and indirectly stimulated by a one unit change in final demand for each sector. This allows for a simplification of Equation (16-7) for cases where only one sector is affected (or where one wishes to isolate the impacts due to changes in one sector) as follows:[3]

$$M_A \Delta Y_A = \Delta X \qquad (16\text{-}8)$$

Under normal circumstances final demand changes will alter household incomes and subsequently consumer spending. Thus, under some uses of input-output techniques, households (broadly defined as the recipients of all income payments) are "endogenized" (included within the A matrix) by treating it as any other sector, i.e., a user (consumer) of outputs and as a supplier of services. An augmented Leontief inverse is computed and yields a set of coefficients, or multipliers, that capture both "indirect" (interindustry) and subsequent "induced" (household income) effects. Multipliers are computed from a matrix with respect to households. These are referred to as Type II multipliers in contrast to the Type I multipliers derived from the "open" I-O table, which excludes households. Of course, since they incorporate an additional set of spending linkages, Type II multipliers are larger than Type I, typically by around 25%.

[3] Note that the previous discussion pertains to demand-side (backward-linked) multipliers. A different set of calculations is required to compute supply-side (forward-linked) multipliers. (Computationally, the structural coefficients of the supply-side model are computed by dividing each element in a given row by the row sum.) Though mathematically symmetric, the two versions of the model are not held in equal regard. There is near universal consensus that demand-side multipliers have merit because there is no question that material input requirements are needed directly and indirectly in the production. However, the supply-side multipliers have a different connotation—that the availability of an input stimulates its very use. To many, this implies the fallacy of "supply creates its own demand." Thus, supply-side multipliers must be used with great caution, if at all, and are not explored at length here. For further discussion of the conceptual and computational weaknesses of the supply-side model, see Oosterhaven (1988) and Rose and Allison (1988).

Note also that the multipliers discussed thus far pertain to output relationships. Multipliers can also be calculated for employment, income, and income distribution effects in analogous ways. Also note that sectoral output multipliers usually have values of between 2.0 and 4.0 at the national level and are lower for regions, progressively shrinking as these entities become less self-sufficient and hence the endogenous cycle of spending is short-circuited by import leakages. Sectoral output multipliers for Suffolk County, the core of the Boston Metropolitan Statistical Area, are for the most part in the range of 1.5 to 2.0.

16.3.2 An Illustration of Backward Linked Losses

Conventional input-output models provide a starting point for measuring indirect damages that are backward-linked, providing that the disaster does not significantly alter the region's input patterns and trade flows. In the next section, we will discuss modifications of the methodology for such changes. The calculation of indirect damages for the more simple case is illustrated in the following example beginning with the input-output transactions matrix presented in Table 16.2.

Table 16.2: Interindustry Transactions

To From	A	B	Households	Other Final Demand	Gross Output
A	20	45	30	5	100
B	40	15	30	65	150
Households	20	60	10	10	100
Imports	20	30	30	0	80
Gross Outlay	100	150	100	80	430

This simplified transactions table is read as follows: $20 of industry A's output is used by itself (e.g., a refinery uses fuel to transform crude oil into gasoline and heating oil). $45 of output A is shipped to industry B. $30 is marketed to the household sector and $5 is sold to government, used in investment, or exported to another region. $20 worth of household services is required to produce $100 of output A, and $60 is needed for $150 of B. According to the table, 30 percent of the consumer's gross outlay is allocated to the purchase of A, 30 percent to B, 10 percent to household services, and 30 percent to imports.

Assume that the input-output tables shown above represent a tourist-based seaside economy. Industry A represents construction while B represents tourism. What would happen to this economy if an earthquake destroyed half the region's beachside hotels? Direct economic losses are comprised of manmade assets destroyed in the earthquake plus the reductions in economic activity[4] in the tourist sector. Assume that the damage to hotels influences some tourists to vacation elsewhere the year of the disaster, reducing the annual $95 million demand for hotel accommodations by $45 million.

For the purposes of this illustration, household spending and demands are linked. Therefore, a Type II multiplier would be utilized to assess the income and output changes anticipated. The effect of declining tourism on the region's economy is easily derived from the initial change in demand and the Type II multipliers presented in Figure 16.3.

[4] Economic activity can be gauged by several indicators. One is Gross Output (sales volume). Another is Value-Added, or Gross National Product (GNP), which measures the contribution to the economy over and above the value of intermediate inputs already produced, thereby avoiding double-counting (note the "Gross" in GNP simply refers to the inclusion of depreciation and differs from double-counting meaning of the term in Gross Output.) Specifically, Value-Added refers to returns to primary factors of production: labor, capital, and natural resources. The concept is identical to the oft used term National Income, which is numerically equal to GNP.

Each tourist dollar <u>not</u> spent results in a loss of $1.20 and $2.03 worth of production from A and B, respectively.

The resultant total (direct plus indirect) decline in regional household income is $1.17 per tourist dollar lost (row 3 column 2 of the closed Leontief Inverse). If nothing else changed (including no pick up in construction activity), the regional income lost for the year is $52.65 million ($45 million times 1.17). Of this total, $18 million (40 cents of lost income for each tourist dollar lost, or .4 times $45 million) is directly traceable to the disaster, while the other $34.65 million in regional income loss represents indirect income losses cause by reduced demands for intermediate goods and consumer items via backward interindustry linkages and normal household spending.

TOTAL COEFFICIENTS (TYPE II MULTIPLIER)

$$\begin{array}{cc} & \begin{array}{ccc} \text{CONSTRUCTION} & \text{TOURISM} & \text{HOUSEHOLD} \end{array} \\ (I-A)^{1-} = & \begin{bmatrix} 2.12 & 1.20 & 1.11 \\ 1.29 & 2.03 & 1.11 \\ 1.04 & \boxed{1.17} & 1.85 \end{bmatrix} \end{array}$$

x $45 MILLION
= $52.65 MILLION
DIRECT, INDIRECT, INDUCED INCOME LOSSES

DIRECT COEFFICIENTS

$$\begin{array}{cc} & \begin{array}{ccc} \text{CONSTRUCTION} & \text{TOURISM} & \text{HOUSEHOLD} \end{array} \\ A = & \begin{bmatrix} .2 & .3 & .3 \\ .4 & .1 & .3 \\ .2 & \boxed{.4} & .1 \end{bmatrix} \end{array}$$

x $45 MILLION
= $18 MILLION
DIRECT INCOME LOSSES

SECONDARY INCOME LOSS = $52.65 MILLION minus $18 MILLION
= $34.65 MILLION

Figure 16.3 Illustrative Computation

16.3.3 The Impact of Outside Reconstruction Aid on the Region and the Nation

Negative effects would be countered by the stimulative impact of state and federal disaster aid and insurance settlements. Whether these positive forces completely offset the negatives produced by the reduction in tourist trade hinges on the magnitude of the direct effects and the associated multipliers for these two activities. Assume, for example, that $50 million of outside reconstruction funds pour into the community in the first year. The Type II income multiplier for the construction industry is 1.04. The net regional income loss the year of the disaster is, therefore: ($50 million x 1.04) - ($45 million x 1.17), or a net loss of $0.65 million.

Indirect income changes in this case are very significant and can be computed as the difference of total income impacts and direct income impacts. We know from the direct coefficients matrix that household income changes directly by 20 and 40 cents, respectively, for each dollar change in construction and tourist expenditures. The net indirect regional impact from the reduction in tourism, and the aid program are therefore: ($50 x 1.04 - $50 x .2) - ($45 x 1.17 - $45 x .4), or a net gain of $7.35 million.

This is what the region loses; however, national impacts are quite different. The $50 million of federal assistance injected into the region must be paid for either by cutting federal programs elsewhere, raising taxes, or borrowing. Each option impacts demand and outputs negatively. Although it is unlikely that they will precisely offset the gains the region enjoys, it is safe to assume that they will be similar in magnitude. If so, indirect losses from a national perspective is the net regional loss <u>with the positive effects from federal aid omitted</u>. The national net income loss will then remain $52.65 million.

The foregoing analysis was limited to the year of the disaster and presupposed that unemployed households did not dip into savings or receive outside assistance in the form of unemployment compensation, both of which are often the case. In terms of the summation of impacts over an extended time horizon, results do not significantly change if alternative possibilities are introduced. For example, if households choose to borrow or utilize savings while unemployed or to self-finance rebuilding, future spending is sacrificed. Therefore, even though an unemployed household may be able to continue to meet expenses throughout the reconstruction period, long-term levels of expenditure and hence product demand, must decline.

In the preceding analysis, indirect losses were derived from demand changes only. This approach lends itself to events in which supply disruptions are minimal, or where sufficient excess capacity exists. A different method is required when direct damage causes supply shortages. The Indirect Loss Module, to which we now turn, modifies the basic I-O methodology to accommodate both supply and demand disruptions.

16.4 The Indirect Loss Module

The foregoing example illustrated how *<u>demand</u>* shocks filter through the economy to produce indirect losses. As indicated, supply shocks require a different treatment. Most *<u>supply</u>* shock models begin with the same trading pattern which produced the A matrix and subsequent multipliers inherent in the input-output method. However, once damage to buildings and lifelines constrain the capacity of each economic sector to ship its output to other sectors, or receive shipments, the trading patterns have to be readjusted. There are several ways to accomplish this. The simplest (Cochrane and Steenson, 1994) is to estimate how much each sector's output will decline as a result of direct damage and then address how the resultant excess demands and/or supplies will be filled and or disposed of. In the event that the sum of all interindustry demands and final demands exceed the post-disaster constraint on production, then available imports and inventory changes could temporarily help to rebalance the economy. In some sectors excess supplies might exist. If so, inventories may be allowed to accumulate or new markets might be found outside the affected region. Surviving production is reallocated according to the interindustry direct coefficients matrix until all sector excess supplies and demands are eliminated. At this point, a new level of regional output, value added and employment is computed and contrasted with the levels observed prior to the disaster. The difference between these levels approximates indirect loss.[5]

16.4.1 Damage -- Linkage to the Direct Loss Module

The Indirect Economic Loss module is linked to preceding modules through three channels in which damage, the direct shock, is introduced. First, building damage causes a certain degree of loss of function to each sector, forcing them to cut output. A vector of loss of function by industry in the first year of the disaster provides a set of constraints to the Indirect Loss module that is related to the general building stock damage levels. Loss of function is based upon the time needed to clean up and repair a facility or to rent an alternative facility to resume business functions (see Section 15.2.4). Loss of function is calculated for each occupancy class. Table 16.3 links the sectors in the Indirect Loss Module to the occupancy classes in the Direct Loss Module. Loss of function associated with lifeline disruption is not evaluated.

Table 16.3 NIBS Occupancy Classes and Indirect Loss Module Economic Sectors

Direct Loss Module	Indirect Loss Module
IND3	Agriculture (Ag)
NONE	Mining (Mine)
IND6	Construction (Cnst)
IND 1,2,3,4,5 (AVG.)	Manufacturing (Mfg)
COM3	Transportation (TRANS)
COM 1,2 (AVG.)	Trade (Trde)
COM 5,4 (AVG.)	Finance, Insurance and Real Estate (FIRE)
(COM 2,4,6,7,8,9; RES 4,6; REL; ED 1,2) (AVG.)	Service (Serv)
GOV1	Government (Govt)
NONE	Miscellaneous (Misc)

Second, post-disaster spending on reconstruction, repair and replacement of damaged buildings and their contents causes a stimulus effect in the Indirect Loss Module. This stimulus is based on the total dollar damage to buildings and contents. Third, reconstruction inputs for transportation and utility lifeline damage also provide a stimulus effect to the module.

Total levels of reconstruction expenditures are equivalent to damage estimates, but two modifications are needed before they can be incorporated into the analysis. One

[5]This approach relies on both the existence of regional input-output tables and several assumptions regarding: inventory management, importability of shortages, exportability of surpluses and the amount of excess capacity existing in each sector. It does not accommodate the effects of relative price changes on final demands, nor does it entertain the degree to which labor and capital are substitutable in the underlying production functions. Treatment of these issues require a more sophisticated approach, one which is discussed in the literature under the topic heading Computable General Equilibrium (CGE) Systems.

modification is the timing of the reconstruction in terms of weeks, months, or years after the earthquake. The distribution of reconstruction expenditures over time is discussed in Section 16.5.1.1 in relation to user inputs to the module.

The other modification is the itemization of expenditures by type (plant, equipment, etc.) so that this spending injection is compatible with the economic model used to determine indirect effects. The input-output (I-O) model at the core of the module disaggregates the economy into sectors according to one-digit Standard Industrial Classification (SIC) codes. The brunt of the reconstruction expenditures will be assigned to Manufacturing and Construction sectors.

One idiosyncrasy of the I-O model is the role of Wholesale and Retail Trade and of Transportation. These sectors are based on the concept of a "margin," i.e., the cost of doing business (labor, insurance, electricity, gasoline, office supplies) plus profits, but does not include the items sold or shipped (which are merely a pass-through in any case).[6] Those expenditures assigned to Construction require no adjustment, but when spending on manufactured goods is inserted into the model, portions of the total should be assigned to the Wholesale/Retail Trade sector and to the Transportation sector. For very large items bought directly from the factory, there is no Trade sector activity, but for smaller items (e.g., office equipment, trucks), the adjustment is necessary. Generally, the Wholesale margin is 80%. Whether purchased from the factory or from the Trade sector, the Transportation margin is always applicable and is typically equal to 20%.

A similar adjustment is necessary in nearly all cases for consumer spending for replacement of contents. In this case, it is more appropriate to use the Retail Trade margin of 80%. Again, the Transportation margin of 20% would be applicable to purchases of larger items.

In cases where the margin adjustment is required, the user simply applies the following formulas:

$$\frac{\Delta L}{1+tm} = \Delta Y_M \tag{16-9}$$

$$\Delta L - \Delta Y_M = \Delta T \tag{16-10}$$

where:

ΔL = Portion of loss estimate (reconstruction/replacement) to which margin adjustment applies.

ΔY_M = Manufacturing expenditures after margin adjustment.

[6]The reason for this device is that many items are sold through wholesale and retail outlets and transported commercially, and, if included as "inputs" to these sectors, the linkage between buyers and sellers would be lost, i.e., it would appear that most purchases were from Wholesale/Retail Trade or Transportation, as if these sectors produced most items in the economy.

ΔT = Retail/wholesale, trade or transportation expenditures.

tm = Retail/wholesale, trade or transportation margin.

16.4.2 Supply-Side Adjustments and Rebalancing the Economy

The Indirect Loss Module is a computational algorithm that utilizes input-output coefficients to reallocate surviving production. The algorithm computes post-event excess demands and supplies. It rebalances the economy by drawing from imports, inventories, and idle capacity when supplies are constrained. It allows for inventory accumulation, production for export (to other regions) and sales to meet reconstruction needs in the event that normal demands are insufficient to absorb excess supplies The process of reallocation is governed by the amount of imbalance detected in each of the economy's sectors. Rebalancing is accomplished iteratively by adjusting production proportionately until the discrepancy between supplies and demands is within a tolerable limit.[7] A simple schematic of the process is provided in Figure 16.4.

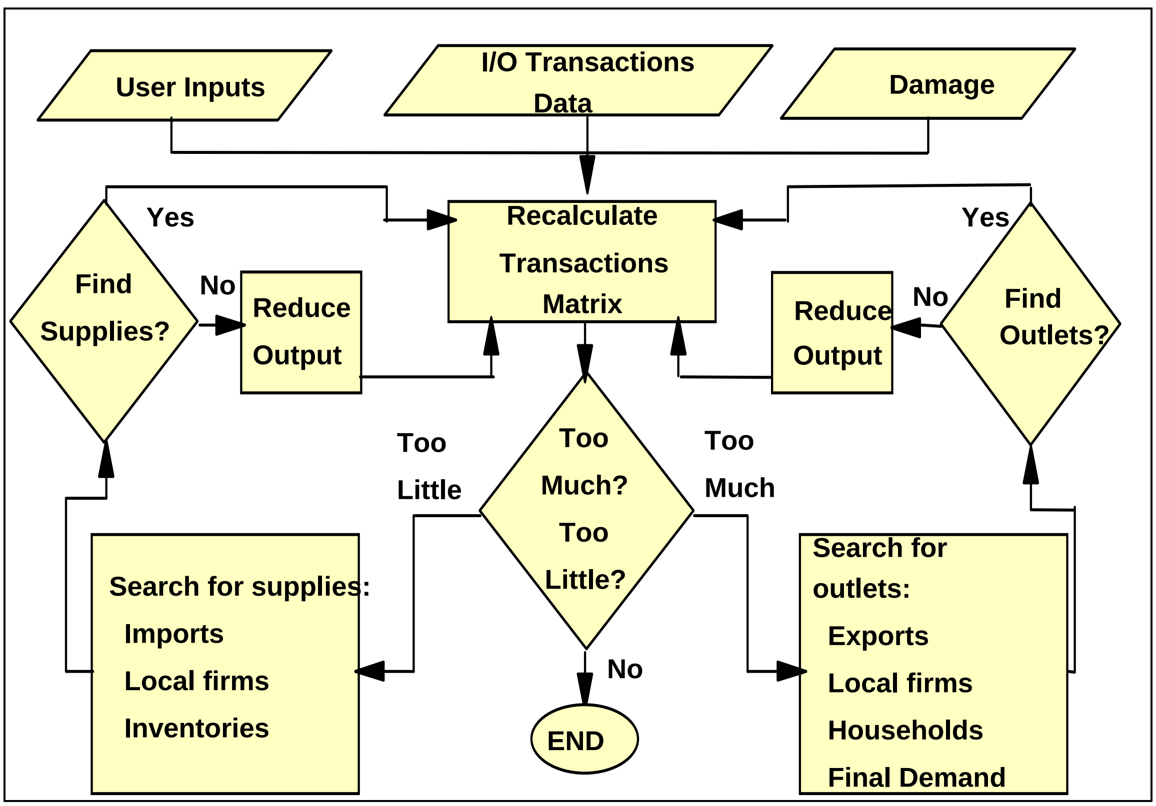

Figure 16.4 Indirect Loss Module Schematic

This section illustrates how the model adjusts to supply-side constraints when a disaster causes disruption in the level and pattern of local production.

[7] The tolerable limit is the degree to which the solution values vary from one iteration to the next.

Table 16.4 illustrates a simple economy with three industries: construction, manufacturing, and trade. There are also two rows for payments to households from those industries and imports which those industries require, plus two columns that represent household demands and exports. Households make no purchases from other households. All amounts in the table are in dollars. In the economy's initial state, the row and column sums are equal.

Table 16.4 Initial Transactions

From/To	Constr	Mfg	Trade	HH	Export	Sum
Constr	10	30	20	20	35	115
Mfg	20	20	10	30	80	160
Trade	15	20	5	40	5	85
HH	30	40	20			90
Import	40	50	30			120
Sum	115	160	85	90	120	

Table 16.5 shows how the economy changes due to the direct impact from a disaster. In this case, there is a 10% loss of manufacturing output as the result of damage to manufacturing facilities. Corresponding to this loss, both the purchases and sales of the manufacturing sector fall by 10%, as reflected in the row and column sums. The transactions directly affected are highlighted in bold type in the table. A new column, named "Lost HH," has been added to this table to reflect manufacturing output that is unavailable to households because of the earthquake.

Table 16.5 10% Direct Loss in Manufacturing

From/To	Constr	**Mfg**	Trade	HH	Export	Sum	Lost HH
Constr	10	**27**	20	20	35	112	
Mfg	**18**	**18**	**9**	**27**	**72**	**144**	**3**
Trade	15	**18**	5	40	5	83	
HH	30	**36**	20			86	
Import	40	**45**	30			115	
Sum	113	**144**	84	87	112		

Table 16.6 illustrates the first example of the indirect response to this situation. This is a "fully-constrained" economy, characterized by no more than 2% unemployment, 0% import replacement, 0% inventory availability or replacement, and 0% additional exports. This means that there are no ways for manufacturers to replace inputs that were disrupted by the disaster.

Under these circumstances, construction and trade firms must cut their previous manufacturing by 10%. There is full employment in the local economy, meaning that other firms in manufacturing cannot increase output to meet the desired purchases by construction and trade. Further imports are not allowed, and there are no inventories of manufacturing output to use. Construction and trade firms, faced with an irreplaceable 10% loss in manufactured goods have no choice but to reduce their production by 10%. The net result is that the 10% direct loss in manufacturing translates into a 10% loss throughout the entire economy. Portions of the table affected by indirect loss are highlighted in italics. The row and column sums are once again in balance. Household consumption is decreased for all three sectors, and there is no way to make up for it.

Table 16.6 Response to Loss with Fully Constrained Economy

From/To	Constr	**Mfg**	Trade	HH	Export	Sum	Lost HH
Constr	*9*	**27**	*18*	*18*	*31.5*	*103.5*	*2*
Mfg	**18**	**18**	**9**	**27**	**72**	**144**	**3**
Trade	*13.5*	**18**	*4.5*	*36*	*4.5*	*76.5*	*4*
HH	*27*	**36**	*18*			*81*	
Import	*36*	**45**	*27*			*108*	
Sum	*103.5*	**144**	*76.5*	*81*	*108*		

The fully constrained economy is an extreme case, and most economies are characterized by some flexibility, or slack, so that inputs can be replaced and outputs can be sold. We illustrate this by raising the potential level of additional imports by 10%, and the potential level of additional exports by 40%. This is insufficient to ensure that construction and trade can acquire the supplies they need to meet local demands and sell products that are no longer being bought by manufacturing.[8] Sectors not suffering direct losses return to their pre-event levels of production.[9] Manufacturing might import additional manufactured inputs where needed to replace its own direct losses, but labor is not available due to the low unemployment rate and the assumption that the temporarily unemployed labor in manufacturing will not be available to other firms in the sector. Manufacturing losses will only be replaced as damaged manufacturing facilities return to production.

In Table 16.7, the underlined values show where the important changes have occurred. Both construction and trade were allowed to import the manufactured inputs they lost as a result of the earthquake. Also, construction and trade exported that portion of their output that manufacturing no longer purchased. Because of these two factors, there is no indirect loss in the case illustrated in Table 16.7.

The same results may be obtained in other ways. Instead of increasing imports, there might be some unemployment in the local economy. In this case, other firms in the manufacturing sector could hire some of the unemployed resources to make up the shortfall. Alternatively, there might be inventories of manufactured goods, either at the manufacturers or in storage at the construction and trade firms that require those goods. On the output side, firms faced with a reduction in purchases from the manufacturing sector may decide to continue production and store the resulting product in inventory until the disrupted facilities are back in production or until they can find new export markets.

[8] Construction only needs to increase its level of imports by 2, 5% of its initial imports of 40, and trade only requires an increase in imports of 1, or 3.3% of 30. Construction requires additional exports of 3, or 8.6% of original exports. The limiting sector is trade, required to find export markets for 2 units, 40% of the 5 units it originally exported.

[9] Even if the slack assumptions are set higher, the algorithm limits sectoral production to be no higher than prior to the earthquake (unless there is a positive counter-stimulus from, say, reconstruction activity).

Table 16.7 Response to Loss with Relaxed Import and Export Constraints

From/To	Constr	**Mfg**	Trade	HH	Export	Sum	Lost HH
Constr	*10*	**27**	*20*	*20*	*38*	*115*	
Mfg	**18**	**18**	**9**	**27**	**72**	144	**3**
Trade	*15*	**18**	*5*	*40*	*7*	*85*	
HH	*30*	**36**	*20*			*86*	
Import	*42*	**45**	*31*			*118*	
Sum	*115*	144	*85*	*87*	*117*		

In Table 16.7, manufacturing remains at its immediate post-disaster level because the situation being illustrated is immediately after the event, before reconstruction can take place. If the slack in the system came from unemployment instead of imports, the results would be different. That portion of the manufacturing sector undamaged by the earthquake could hire additional resources and make up the direct losses. Overall production would regain its pre-disaster levels. Therefore, unlike the example illustrated which shows no net indirect change, there would be a net indirect increase in sales that would be equal to the direct loss, making for a net economic change of zero.

Tables 16.6 and 16.7 show an important way in which this algorithm departs from traditional I-O analysis. The technical coefficients for both Tables are different from those of the original economy. This is because imports and exports have been allowed to replace lost supplies and sales in the system. The usual technical coefficients in an I-O table assume that the relationships between imports and intermediate inputs are fixed, as well as assuming that the relationships between exports and intermediate outputs are fixed. Though these assumptions are convenient for the purposes of I-O analysis, they are a departure from reality in general, and especially so in emergency situations. Also note, from Table 16.7, that the household and import/export sectors are no longer balanced in terms of row and column sums. This is due to the short-run nature of the problems being solved in the model. In the longer run, households must repay their borrowing, and exports must rise to repay the short-run imports, unless government disaster aid or some other form of external financing is used to pay for the short-run consumption and imports.

Tables 16.6 and 16.7 illustrate the two extremes that the model can reflect in responding to pure supply-side disruptions. In its fully functional implementation, the model adjusts simultaneously for multiple shocks of varying amplitude in any number of sectors, while also accounting for demand-side (final demand) increases that typically accompany disasters.

16.4.3 The Time Dimension

The model is evaluated at various levels of temporal resolution for the fifteen (15) year period following the earthquake. For the first two (2) months after the earthquake, weekly time intervals are used. Between two (2) months and twenty four (24) months, the economy is evaluated on a monthly basis. From two (2) years to fifteen (15) years, the economy is evaluated annually. It is made dynamic by considering how industry loss of function is restored and reconstruction expenditures are made over the time windows. Thus while the inputs to the Indirect Economic Loss module differ with each time interval, the rebalancing algorithm for the economy and adjustment factors (e.g., availability of supplemental imports to make up for lost production) do not change. The time patterns of functional restoration and reconstruction are user inputs and are discussed in Section 16.5.

16.4.4 The Effects of Rebuilding and Borrowing

Borrowing impacts the model in that future demands are reduced in proportion to the temporal payments for rebuilding. In the case of Northridge this amounted to less than 50 percent. Federal assistance and insurance settlements provided the bulk of the financial resources for reconstruction. The importance of refinancing lies in longer-term effects of repayment. If the affected region receives no assistance then the stimulative effects of rebuilding are only temporary. The region will eventually have to repay loans and future spending will suffer. This is accounted for in the model as follows.

1. It is assumed that all loans mature 15 years *from the time of the earthquake*. Therefore, the first year's loans are for 15 years. The second year's loans are for 14 years, and so on.
2. Tax implications are ignored. Interest is not tax deductible.
3. Borrowing costs are assumed to be 6 percent. This is a real interest rate (inflation free). The discount rate is assumed to be 3 percent. It too is inflation free.

The loan payments are computed as follows (Table 16.8).

Table 16.8 Annual Borrowing Costs

Year	1	2 through 15
Annual Payment	$\left[\frac{r}{(1-(1+r)^{(-15+1)})}\right] loan1$	$\left[\frac{r}{(1-(1+r)^{(-16+t+1)})}\right] loan_t + Pay_{t-1}$
Explanation	loan 1 times the annual payment factor (r is real interest)	payment from t-1 plus loan t times the annual payment factor

Future demands are reduced by the annual payments times the percentage households spend on each sector's output. For example, if households are paying back \$50 million in year 1 then spending from all categories decline as shown in the following table. The second column in Table 16.9 is the pre-disaster spending pattern. For example, 0.2 percent of household income was spent on agricultural products; 24.6 percent was spent on services. This percentage times $50 million loan repayment cost yields the reduction in household spending by sector in year 1.

Table 16.9 The Effect of Loan Repayment on Household Demands

Sector	Household Spending (% spent on each sector)	Reduced Demand in $ millions (% times loan payment)
Ag	0.2%	0.08
Mine	0.0%	0
Cnst	11.2%	5.59
Mfg	7.5%	3.75
Trns	6.2%	3.08
Trde	21.6%	10.82
FIRE	23.2%	11.59
Serv	24.6%	12.3
Govt	5.3%	2.63
Misc	0.3%	0.15

Exercising the module sequentially using average values over the reconstruction period derives time dependent indirect losses.

16.4.5 The Issue of Aggregation

Study regions may consist of single counties, higher levels of aggregation such as several counties comprising a metropolitan area, or lower levels of aggregation such as a group of contiguous census tracts. In principal, the methodology underlying the Indirect Economic Loss module is applicable regardless of the level of aggregation. However, its accuracy is likely to be greater for study regions that represent cohesive economic regions, often called “trading areas” (e.g., cities or metropolitan areas) than for those at lower levels of aggregation because of the ability of the core Input-Output model to meaningfully represent the region’s economic structure. Furthermore, in evaluating regional employment impacts, the module requires input data on the number of jobs located within the study region -- that is, data on employment by place of work rather than by place of residence. While this information can be obtained at the county level, its availability and reliability at lower levels of aggregation are much more problematic. Similar problems are associated with other input data such as unemployment rates. More generally, the user should also be aware that some of the input assumptions to the model (such as the availability of alternate markets) are related to the study region’s level of aggregation. By adjusting the nature of the economy and the linkage to surrounding regions, the analyst can get a “ball park” estimate of what the real indirect losses and gains might be. Tracing the effects to a specific geographic area (beyond that directly impacted by the earthquake) is problematic. Section 16.5 below provides some discussion of appropriate input data and assumptions to the module.

16.5 Running the Module

This section describes operational issues related to the methodology's Indirect Economic Loss module, including data inputs, the operation of the software module, and the format and interpretation of the output. Default Data Analysis utilizes primarily default data and requires minimal user input. In User-Supplied Data Analysis, while the same types of data are required, the user provides information specific to the economy of the study region and the disaster being modeled. Advanced Data and Models analysis assumes expert participation and may involve expanding the module framework or applying alternative frameworks.

16.5.1 Default Data Analysis Inputs, Operation and Output

16.5.1.1 User Inputs and Default Data

Running the Indirect Economic Loss module requires a number of user inputs. While default values are provided for all of these inputs, as discussed below, it is advisable even in a Default Data Analysis to override certain of them with data for the study region where available. Table 16.10 describes the inputs required and their default values.

The methodology provides default values for the current employment based on Dun & Bradstreet data and income levels for the region based on County Business Pattern data. Note that in contrast to some other sources of regional employment data, this estimate of workers represents the number of persons who work within the study region, rather than the number of employed persons who reside there. Employment by place of work is appropriate in this type of analysis because the model will estimate job loss within the study region due to physical damage there from the disaster. It is recommended that the Default Data Analysis user review the default values provided and replace them if more accurate or recent data is available. Note that in User-Supplied Data Analysis, where a user-provided IMPLAN Input-Output table is used instead of a synthetic table, the current employment and income levels are read in from the IMPLAN files and override the default values.

The type or composition of the economy, together with the employment level, is used by the module to automatically select a synthetic Input-Output transactions table to represent the study region economy. Default Data Analysis utilizes a synthetic transactions table aggregated from three basic classes of economies: 1) primarily manufacturing, 2) primarily service, secondarily manufacturing, and 3) primarily service, secondarily trade. These 3 archetypical economies represent approximately 90 percent of the 113 transactions tables used to construct the three synthetic tables. Each type is broken into four size classifications: super (greater than 2 million in employment), large (greater than 0.6 million but less than 2 million), mid range (greater than 30 thousand but less than .6 million) and low (less than 30 thousand). Appendix 16A provides examples of regions in each type and size class. While type 1 (manufacturing) is the default, the user should revise this as appropriate. Appendix Tables A2, A3, and A4 can be used as a guide.

Supplemental imports, inventories (demands), inventories (supplies), and new export markets represent available channels for excess supply or demand that can help reduce the bottleneck effects in the post-disaster economy. As mentioned above, appropriate values depend in part on the level of aggregation of the study region. Default values are set at 0 for inventories supply and demand for all industries. Default values for imports and exports are set at values considered appropriate for a "distinct" or self-contained study region such as a metropolitan area. The default values are presented, together with discussion of how they can be modified in a User-Supplied Data Analysis, in Section 16.5.2.2.

The supplemental imports variable, due to limitations on available data, needs further explanation. Data on the amount of imports per sector are available only in the aggregate. For any one sector in the economy, the total amount of intermediate products imported is known, but the amount of these imports that comes from any individual sector is not known. The amount of new imports that may be allowed must be set to a very small level. Otherwise, the amount of products that may be imported will almost always replace any intermediate goods lost from local suppliers, and no indirect output losses will be observed. The level of supplemental imports also needs to be kept low because of factor homogeneity problems. There will be cases when there are no substitutes for locally obtained intermediate goods. In such cases, allowing imports would unreasonably eliminate indirect losses. Being conservative in the amount of imports allowed helps avoid both of these problems. The default values for imports have been tested in the model, and are felt to yield realistic results.

Table 16.10 User Supplied Inputs for Indirect Economic Module

Variable	Definition	Units[(a)]	Default Value
Current Level of Employment	The number of people gainfully employed, by place of work (not residence).	Employed persons	Region-specific
Current Level of Income	Total personal income for the study region.	Million dollars	Region-specific
Composition of the Economy (Default Data Analysis only)	1. Primarily manufacturing 2. Primarily service, secondarily manufacturing. 3. Primarily service, secondarily trade.	1, 2, or 3	1
Supplemental Imports	In the event of a shortage, the amount of an immediate product unavailable from local suppliers which may be obtained from new imports.	Percent of current total current annual imports (by industry)	Defaults for "distinct region"
Inventories (Supplies)	In the event of a shortage, the amount of a good that was supplied from within a region that can be drawn from inventories within the region.	Percent of annual sales (by industry)	0 (for all industries)
Inventories (Demand)	In the event of a surplus, the amount of a good placed in inventory for future sale.	Percent of current annual sales (by industry)	0 (for all industries)
New Export Markets	In the event of a surplus, the amount of a good which was once sold within the region that is now exported elsewhere.	Percent of current annual exports (by industry)	Defaults for "distinct region"
Percent Rebuilding	The percent of damaged structures that are repaired or replaced	Percent	95%
Unemployment Rate	The pre-event unemployment rate as reported by the U.S. Bureau of Labor Statistics	Percent	6%

Outside Aid/Insurance	The percentage of reconstruction expenditures that will be financed by Federal/State aid (grants) and insurance payouts.	Percent	50%
Interest Rate	Current market interest rate for commercial loans.	Percent	5%
Restoration of function	The percent of total annual production capacity that is lost due to direct physical damage, taking into account reconstruction progress.	Percent (by industry, by time interval for 5 years)	Defaults for moderate-major event
Rebuilding (buildings)	The percent of total building repair and reconstruction that takes place in a specific year.	Percent (by time interval for 5 years)	56% (yr.1), 36% (yr.2) 10% (yr.3)
Rebuilding (lifelines)	The percent of total transportation and utility lifeline repair and reconstruction that takes place in a specific year.	Percent (by time interval for 5 years)	70% (yr.1), 25% (yr.2) 5% (yr.3)
Stimulus	The amount of reconstruction stimulus anticipated in addition to buildings and lifelines repair and reconstruction.	Percent (by industry, by Time interval for 5 years)	0% (for all)

Notes: (a) Percent data should be entered as percentage points, e.g. 60 for 60%.
(b) The methodology provides a default value for the counties in the study region.
(c) See Section 16.5.2.2.

The variables for percent rebuilding, unemployment rate, percent outside aid, and interest rate all influence how the economy is expected to react to the disaster, in particular the reconstruction stimulus, the available slack or unused capacity in the economy, and the associated indebtedness that would be incurred from reconstruction financing. The user is recommended to revise the unemployment and interest rates as appropriate. However, all of these variables can be adjusted for purposes of "what-if" scenario modeling. For example, how would regional indirect economic losses change if only 20 percent of reconstruction was financed by sources outside the region such as insurance or federal disaster aid?

Parameters for functional restoration, as well as rebuilding for both buildings and lifelines, are associated with the anticipated speed of reconstruction and recovery. To specify functional restoration, user inputs are required for the percent of each industry's production capacity that is lost as a result of physical damage in each year for the first 5 years after the disaster. Default parameters are provided that are designed to be consistent with a "moderate-to-major" scale of disaster. These parameter values and suggestions for modifying them in a User-Supplied Data Analysis are provided in Section 16.5.2.2 below.

In terms of rebuilding, the module requires user inputs as to the percent of total rebuilding expenditures for buildings and lifelines respectively that are expected to be made in each of the first 5 years following the disaster. Table 16.11 provides an example. Note that the total dollar amount required to fully rebuild damaged and destroyed public and private capital is provided by the Direct Economic Loss module. The percent of this total that is actually rebuilt is specified by the user input on "percent rebuilding" and may be less than 100 percent if not all of the damage is repaired or replaced. The annual percents for rebuilding buildings and lifelines as shown in Table 16.11 provide the timeline over which the reconstruction expenditures are made and should therefore sum to 100 percent over the 5-year period.

Table 16.11 Rebuilding Expenditures Example

Year	1	2	3	4	5	Total
% of Total Rebuilding Expenditures (Buildings)	54	36	10	0	0	100
% of Total Rebuilding Expenditures (Lifelines)	70	25	5	0	0	100

Reconstruction speed is also to a large extent related to the scale of the disaster. In general, lifeline reconstruction is expected to proceed much more quickly than building reconstruction, as has been the experience in previous disasters. For a Default Data Analysis, default parameters are provided that are designed to be consistent with a "moderate-to-major" scale of disaster. Modifying these parameters would be appropriate in a User-Supplied Data Analysis, and guidelines are provided in Section 16.5.2.2 below. These parameters can also be adjusted in Default Data Analysis for purposes of "what-if" scenario modeling for faster or slower paces of reconstruction.

The additional reconstruction stimulus parameters can also be adjusted for "what-if" evaluations.

16.5.1.2 Calculation of Indirect Loss

A direct shock is introduced into the Indirect Loss Module by adjusting the outputs and purchases in proportion to a sector's loss of function. Restrictions on shipments (forward linkages) and purchases (backward linkages) are computed and the resultant excess demands or supplies are derived. See Figure 16.5. The sample transactions table provided in Table 16.20 (Section 16.6.2) is used to illustrate. The first two rows above the table indicate the total direct shock and associated indirect losses, which are initially zero. The first round effects are simply the direct loss of function times the inputs to that sector (backward links) and shipments from that sector (forward links). In the event of a 30 percent loss of function in the transportation sector, for example, demand for manufactured goods would fall by 15.6 (0.3 times 51.9). The remainder of the column effects is computed similarly.

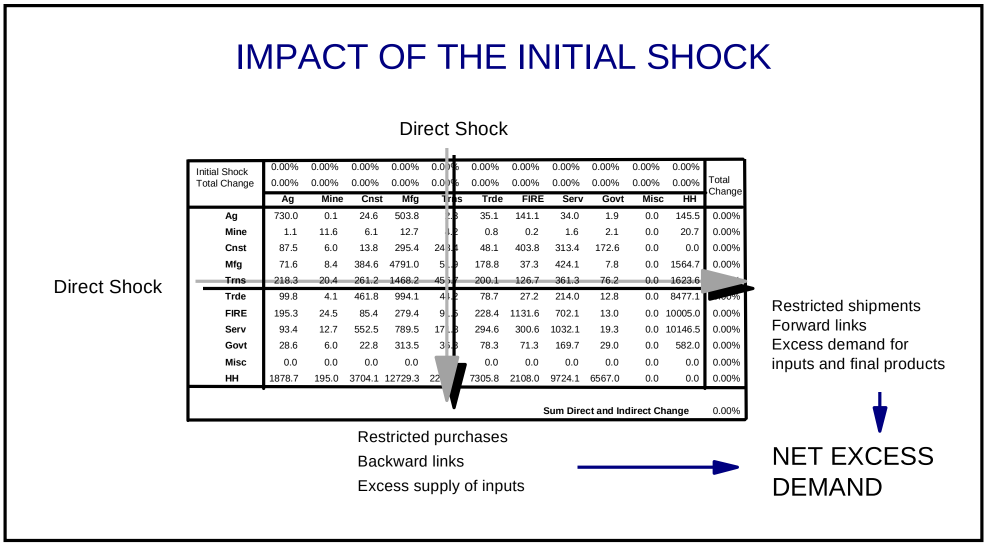

Figure 16.5 Initial Effects of the Shock

The same 30 percent shock would limit shipments to other sectors; finance, insurance, and real estate, for example, will initially receive 38.0 less (0.3 times 126.7) in services from transportation.

These first round effects produce excess demands and supplies that trigger a search for markets and alternative supply sources.

In building the model, several critical choices had to be made regarding post-event household spending patterns, labor mobility, elasticity of supplies from the construction industry, and the potential for product substitutions due to relative price changes. Evidence from previous disasters (summarized in the User's Manual) suggests that: 1) normal spending patterns are not significantly altered; 2) the workforce is highly mobile, particularly in the construction sector; and 3) relative prices do not change appreciably. Therefore, labor and construction sales are not constrained, and normal household spending is fixed and independent of current income. Given these conditions, the model assesses the net excess supplies (output less the sum of intermediate and final demands). A positive net value implies an excess supply; a negative indicates excess demand. It then attempts to resolve sectoral imbalances through a series of adjustments. If excess demand is detected, the algorithm checks to see if sufficient capacity exists in a sector. Excess capacities are a function of user defined level of unemployment and is calculated within the model using the following equation.

$$AC = 2.36 \times (UR - .02) \tag{16-11}$$

Where:

AC is available production capacity and expressed as a percentage (measured as a decimal) of the pre-event capacity

UR is the unemployment rate (e.g., .05).

If idle capacity is insufficient to meet excess demand then the model explores the potential of importing and/or drawing down inventories. These options are also provided by the user and are expressed as a percent of pre-event capacities.

Disposal of excess supplies is logically similar. Two options, inventory accumulation and exports, are explored. As in the case of the previous options, both are expressed as a percentage and are determined by the user. In most cases excess supplies are not critical to the model's, operation, particularly when reconstruction spending looms large. Much of the excesses are drawn into the rebuilding process.

After completing the first iteration of output adjustments, the algorithm recalculates the intermediate supplies and demands and then reinvestigates the adjustment options previously explored. Outputs are revised in proportion to the amount each sector is out of balance. A moving average of previously attempted outputs is used to initialize each iteration's search. The search is terminated once the sum of the absolute sectoral output differences diminishes to a specified level; the default is set at .00001.

Indirect income loss is calculated as using the following formula.

$$\sum_{t=1}^{T} \sum_{i=1}^{j} \frac{(td_{i,t} - dd_{i,t})Y_i}{(1+r)^t} \tag{16-12}$$

where: $td_{i,t}$ is the total percent reduction in sector i income during period t.
Y_t is income of sector i.
$dd_{i,t}$ is the direct percent reduction in sector i income during period t.
r is the real interest rate to discount the indirect losses
j is the number of sectors

dd is computed in the model by multiplying the initial sectoral income by the respective loss of function. The variable td is the total percentage reduction in income caused by the combination of direct loss and forward and backward linked losses. The difference between the two is then the percentage reduction in income attributable to indirect effects. The difference is pure indirect loss. This percentage when multiplied by sectoral incomes yields indirect income lost. A similar formula to Equation 16-12, without discounting, is used to evaluate indirect employment loss.

16.5.1.3 The Format of the Output

The module produces two reports on the results. The first provides the percent and level of indirect economic impact for the study region economy in terms of employment and income effects for a region that receives outside aid after the disaster. Note that impacts may be either losses (negative numbers) or gains (positive numbers). Results are given by time interval for the first 5 years. Average figures are also provided for years 6 to 15. All incomes are discounted at the rate of 3 percent. In the case of income, Year 6 to Year 15 losses or gains are discounted to the present. Employment loss or gains are shown as numbers of workers.

Table 16.12 Summary Tables for Indirect Economic Impact

	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6 to 15
% Net Indirect Employment Impact						
% Net Indirect Income Impact						
Net Indirect Employment Impact						
Net Indirect Income Impact in Millions $						

The second report provides the percent and level of indirect economic impact for the study region economy in terms of employment and income effects for a region that does not receive outside aid after the disaster. Differences in impacts and recovery trends typically are very significant between industries, in part because much of the gains from the reconstruction stimulus accrues to the construction industry (and to some extent the manufacturing and trade industries).

It is important to note that to get a complete picture of the economic impact of the disaster, both the direct and indirect economic losses or gains should be considered.

16.5.2 User-Supplied Data Analysis

This level of Analysis differs from the Default Data level of analysis in two main respects: (1) interindustry trade flows, as represented in the Input-Output model of the economy, and (2) specification of restoration and rebuilding parameters. Rather than selecting from built-in synthetic Input-Output transactions tables, the user should obtain specific tables for the study region from a standard source, the Minnesota IMPLAN Group. In terms of specifying restoration and rebuilding parameters, the user can replace the built-in data with suggested parameter "packages" appropriate to the disaster being modeled. In addition, other parameters such as the availability of supplementary imports can also be modified.

16.5.2.1 IMPLAN Input-Output Data

The methodology requires five files from the IMPLAN input-output data set: The required files are as follows:

- Household Industry Demand (II031).txt
- Industry Output-Outlay Summary (II050).txt
- Institution Industry Demand (II030).txt
- Output, VA, Employment (SA050).txt
- Regional Industry x Industry (Text502).txt

Details regarding the operation of the IMPLAN program and the construction of these files can be obtained from the technical documentation for the system. IMPLAN is currently sold and supported by the Minnesota IMPLAN Group; the Group can be reached at:

- Minnesota IMPLAN Group, Inc.
- 1725 Tower Drive West: Suite 140
- Stillwater, MN 55082
- Phone: 651-439-4421
- Fax: 651-439-4813
- Web site: http://www.implan.com.

Software and data for any county in the United States can be obtained from the IMPLAN group. When requesting data, regions can also be defined by specifying a zip code aggregation.

The user can either request the five data files for the study region from MIG or obtain the software and database to construct the files. In the former case, the user should specify that the required industry aggregation scheme is essentially a one-digit Standard Industrial Classification (SIC) grouping that maps detailed IMPLAN industries into the ten industry groups used in the methodology. Table 16.13 describes the correspondence between IMPLAN and the methodology's industry classes.

Table 16.13 Industry Classification Bridge Table

IMPLAN	**Hazus Methodology**
1-27	AG (Agriculture)
28-47	MINE (Mining)
48-57	CNST (Construction)
58-432	MFG (Manufacturing)
433-446	TRNS (Transportation)
447-455	TRDE (Trade)
456-462	FIRE (Finance, Insurance and Real Estate)
463-509	SERV (Service)
510-523	GOVT (Government)
524	MISC (Miscellaneous)

If the user obtains the IMPLAN software, the three data files can be constructed by following the instructions and constructing an aggregated Input-Output account using an existing or built-in template for 1-digit SIC classification.

16.5.2.2 Specifying Indirect Loss Factors

In addition to applying IMPLAN Input-Output data for the study region, a User-Supplied Data Analysis can involve adjusting module parameters to more closely fit the study region and disaster being modeled. Parameter sets and selection algorithms are suggested below for both the four indirect loss "factors" -- supplemental imports, new export markets, inventories supply, and inventories demand -- and industry restoration and rebuilding.

As previously noted in the Default Data Analysis discussion, availability of supplemental imports and new export markets is related in part to the size or level of aggregation of the study region and its geographic situation. A single county making up part of a large metropolitan area would have a much higher new import/export capacity (i.e., to neighboring counties) than would a single-county city that was geographically a distinct urban area and at some distance from other urban areas. Table 16.14 suggests two possible sets of factor values for geographically "distinct" and "component" study regions based on expert opinion.

Table 16.14 Suggested Indirect Economic Loss Factors
(percentage points)

Industry	Distinct Region				Component Region			
	Imports	Inv. Supply	Inv. Demand	Exports	Imports	Inv. Supply	Inv. Demand	Exports
AGR	5	0	0	20	6	0	0	35
MINE	5	0	0	30	6	0	0	45
CON	999	0	0	10	999	0	0	25
MFG	4	1	1	30	6	1	1	45
TRNS	2	0	0	0	4	0	0	0
TRDE	3	1	1	0	5	1	1	0
FIRE	3	0	0	0	5	0	0	0
SVC	3	0	0	0	5	0	0	0
GOVT	3	0	0	0	5	0	0	0
OTHER	4	0	0	0	6	0	0	0

Selection of appropriate restoration and rebuilding parameters presents a more complex problem because of the need to link these values to physical damage levels in the disaster. Industry functional restoration and rebuilding will generally proceed more slowly with increasing severity of the disaster and extent of physical damage. For this reason, it is recommended that to run a User-Supplied Data Analysis for Indirect Economic Loss that the user first complete a comprehensive analysis, examine the damage results, modify the restoration and rebuilding parameters as appropriate, and then finally run the Indirect Loss module. Several example restoration and rebuilding parameter sets designed based on expert opinion to represent different scales of disaster are presented below, together with a suggested algorithm for the user to select the most appropriate one.

The following suggested procedure attempts to provide a rough but simple and credible link between restoration and rebuilding parameters in the Indirect Loss module and methodology results on physical damage. Lifeline rebuilding and transportation industry functional restoration are linked to highway bridge damage. Manufacturing industry restoration is linked to industrial building damage. Buildings rebuilding and restoration for all other industries is linked to commercial building damage. The values of the industry functional restoration parameters are intended to reflect not only facility damage levels but also each industry's resiliency to damage to its facilities, such as for example its ability to relocate or utilize alternative facilities. These parameters were derived judgmentally with consideration of observations from previous disasters. Note that values for "restoration" represent the percent *loss of industry function* averaged over the specified time window.

STEP 1. Calculate damage indices for highway bridges and commercial and industrial buildings, respectively. The damage index consists of the percent of structures in the "extensive" or "complete" damage states. For example, if results indicate that 5 percent of bridges will suffer "extensive" damage and 3 percent "complete" damage, the damage index is 8 percent. Damage results for bridges can be found in the **Hazus** summary report on Transportation Highway Bridge Damage. Damage results for commercial and industrial buildings can be found in the **Hazus** summary report on Building Damage by General Occupancy.

STEP 2. Select transportation industry restoration parameters and rebuilding parameters for lifelines. Use the highway bridge damage index from Step 1 to read off parameters from Table 16.15.

STEP 3. Select manufacturing industry restoration parameters. Use the industrial building damage index from Step 1 to read off parameters from Table 16.16.

STEP 4. Select restoration parameters for all other industries and rebuilding parameters for buildings. Use the commercial building damage index from Step 1 to read off parameters from Table 16.17.

Table 16.15 Transportation Restoration and Lifeline Rebuilding Parameters
(percentage points)

Highway bridge damage index	Impact description	Parameter Set	Year 1	Year 2	Year 3	Year 4	Year 5
0%	None/ minimal	Restoration function - TRNS Ind.	0	0	0	0	0
		Rebuilding expenditures - Lifelines	100	0	0	0	0
0-1%	Minor	Restoration function - TRNS Ind.	2	0	0	0	0
		Rebuilding expenditures - Lifelines	100	0	0	0	0
1-5%	Moderate	Restoration function - TRNS Ind.	5	0	0	0	0
		Rebuilding expenditures - Lifelines	95	5	0	0	0
5-10%	Mod.-major	Restoration function - TRNS Ind.	10	2	0	0	0
		Rebuilding expenditures - Lifelines	90	10	0	0	0
10-20%	Major	Restoration function - TRNS Ind.	15	3	0	0	0
		Rebuilding expenditures - Lifelines	85	15	0	0	0
>20%	Catastrophic	Restoration function - TRNS Ind.	20	5	0	0	0
		Rebuilding expenditures - Lifelines	80	20	0	0	0

Table 16.16 Manufacturing Restoration Parameters
(percentage points)

Industrial building damage index	Impact description	Parameter Set	Year 1	Year 2	Year 3	Year 4	Year 5
0%	None/minor	Restoration function - MFG Ind.	1	0	0	0	0
0-1%	Moderate	Restoration function - MFG Ind.	2	0	0	0	0
1-5%	Mod.-major	Restoration function - MFG Ind.	4	0	0	0	0
5-10%	Major	Restoration function - MFG Ind.	8	2	0	0	0
>10%	Catastrophic	Restoration function - MFG Ind.	20	10	5	0	0

Table 16.17 All Other Industries Restoration and Buildings Rebuilding Parameters
(percentage points)

Commercial bldg. damage index	Impact description	Parameter Set	Year 1	Year 2	Year 3	Year 4	Year 5
0%	None/minor	Restoration function - AG Ind.	0	0	0	0	0
		Restoration function - MINE Ind.	0	0	0	0	0
		Restoration function - CNST Ind.	0	0	0	0	0
		Restoration function - TRDE Ind.	1	0	0	0	0
		Restoration function - FIRE Ind.	0	0	0	0	0
		Restoration function - SERV Ind.	1	0	0	0	0
		Restoration function - GOVT Ind.	1	0	0	0	0
		Restoration function - MISC Ind.	1	0	0	0	0
		Rebuilding expenditures - buildings	100	0	0	0	0
0-1%	Moderate	Restoration function - AG Ind.	0	0	0	0	0
		Restoration function - MINE Ind.	0	0	0	0	0
		Restoration function - CNST Ind.	1	0	0	0	0
		Restoration function - TRDE Ind.	2	0	0	0	0
		Restoration function - FIRE Ind.	1	0	0	0	0
		Restoration function - SERV Ind.	2	0	0	0	0
		Restoration function - GOVT Ind.	2	0	0	0	0
		Restoration function - MISC Ind.	2	0	0	0	0
		Rebuilding expenditures - buildings	80	20	0	0	0
1-5%	Mod.-major	Restoration function - AG Ind.	0	0	0	0	0
		Restoration function - MINE Ind.	0	0	0	0	0
		Restoration function - CNST Ind.	2	0	0	0	0
		Restoration function - TRDE Ind.	4	0	0	0	0
		Restoration function - FIRE Ind.	2	0	0	0	0
		Restoration function - SERV Ind.	4	0	0	0	0
		Restoration function - GOVT Ind.	4	0	0	0	0
		Restoration function - MISC Ind.	4	0	0	0	0
		Rebuilding expenditures - buildings	70	30	0	0	0
5-10%	Major	Restoration function - AG Ind.	1	0	0	0	0
		Restoration function - MINE Ind.	1	0	0	0	0
		Restoration function - CNST Ind.	4	0	0	0	0
		Restoration function - TRDE Ind.	8	2	0	0	0
		Restoration function - FIRE Ind.	4	0	0	0	0
		Restoration function - SERV Ind.	8	2	0	0	0
		Restoration function - GOVT Ind.	8	2	0	0	0
		Restoration function - MISC Ind.	8	2	0	0	0
		Rebuilding expenditures - buildings	60	30	10	0	0
>10%	Catastrophic	Restoration function - AG Ind.	2	0	0	0	0
		Restoration function - MINE Ind.	2	0	0	0	0
		Restoration function - CNST Ind.	10	5	0	0	0
		Restoration function - TRDE Ind.	20	10	5	0	0
		Restoration function - FIRE Ind.	10	5	0	0	0
		Restoration function - SERV Ind.	20	10	5	0	0
		Restoration function - GOVT Ind.	20	10	5	0	0
		Restoration function - MISC Ind.	20	10	5	0	0
		Rebuilding expenditures - buildings	50	30	15	5	0

16.5.3 Advanced Data and Models Analysis

For this level of analysis, it is presumed that an economist with experience in the economics of natural hazards will be conducting the study.

16.5.3.1 Extending the Indirect Loss Module

The Indirect Loss Module above holds great potential for further development. Some of the alterations that could be incorporated are:

1. Expand the number of industries to better reflect building classes and individual lifelines.

2. Investigate the implications of how shortages and surpluses are addressed. The current Module follows a particular sequence for alleviating bottlenecks; it is possible that this sequence may influence the final results. As currently programmed, the algorithm attempts to resolve shortfalls by looking first to regional excess capacities. In some instances it may be more realistic to expect local producers to look to imports as a source of replacement. There is no obvious *a priori* way of knowing which alternative will be chosen. The particular sequence currently imbedded in the program will tend to maximize production at the local level and therefore minimize the indirect losses associated with an earthquake.

   A more appealing method would be to randomize the priority in which different avenues of ameliorating bottlenecks are chosen. Under this regime, the entire modeling process would be imbedded in a larger iterative loop that could explore a full range of options. By so doing, the robustness of the solution set can be assessed.

   Alternatively, survey research might be conducted which would ascertain how producers might actually respond to an earthquake. The model could then be modified to reflect this information.

3. Make parameter values sector specific. Currently, the methodology is designed so that the supply and demand options (imports, exports, capacity, and inventory adjustments) are identical across sectors. The next logical step would be to make these adjustments sector dependent. This would allow the analyst to better tailor the model to the circumstances of a particular location. For instance, if industry A required the output of industry B, and no substitutes or imports were permitted, a matrix of import probabilities would assign 0% at the intersection of these two industries.

   Additionally, such matrices would allow for consideration of instances where different industries have dissimilar responses to changes in the same input. If industry A requires a large amount of input C, while industry B requires a smaller amount, industry B would be more likely to pay a premium to import input C.

Although this notion seems daunting, it might be possible to incorporate the parameter matrix idea without making the modeling process totally infeasible. For example, one might begin by assigning a scalar, say 10%, to the entire matrix of import probabilities. Then, entire industries could be modified by inputting vectors of new values to those industries. Finally, key intersections for the local economy could be located and specific parameters applied to those intersections. Therefore, at its simplest level, the parameter matrix concept is no more complex than what is currently programmed into the Indirect Loss Module.

4. Approximate price effects. A common complaint leveled against I/O models is that they do not incorporate prices. While this is true, a couple of points need to be made in reference to this particular Loss Module. Significant relative price changes have not been observed after disaster. This may be due in part to special circumstances emerging during the post-disaster period, where price “gouging" is frowned upon, or made illegal (as in Los Angeles after the Northridge earthquake).

However, if concerns about price effects remain, it should be possible to modify the Module accordingly. As the system is currently configured, there are fixed constraints on output, imports, etc. In a supply and demand framework, these could be thought of as a series of discontinuous supply curves which are horizontal until the quantity constraint is reached, at which point they turn perfectly vertical. Enhancement of this system with a function that reduces output as new input sources are tapped would mimic a price-sensitive supply function. However, it must be pointed out that parameterization of such functions is an extremely difficult task. This is one of the problems that Computable General Equilibrium models also face.

5. Extend the model to asses indirect loss/gain incurred by surrounding regions and the national economy. As it now stands, the model is best suited to analysis of the immediately impacted region. However, as pointed out early in the Chapter, regional consequences may be quite different than that measured at the national level. Figure 16.19 indicates how the module could be extended to account for these broader economic linkages. Direct damages and subsequent indirect loss is transmitted to other regions via changes in the import-export relationships. The national economy is impacted in that external aid has to be financed, either at the expense of canceled federal projects, or increased tax liability. In either case demands elsewhere will suffer.

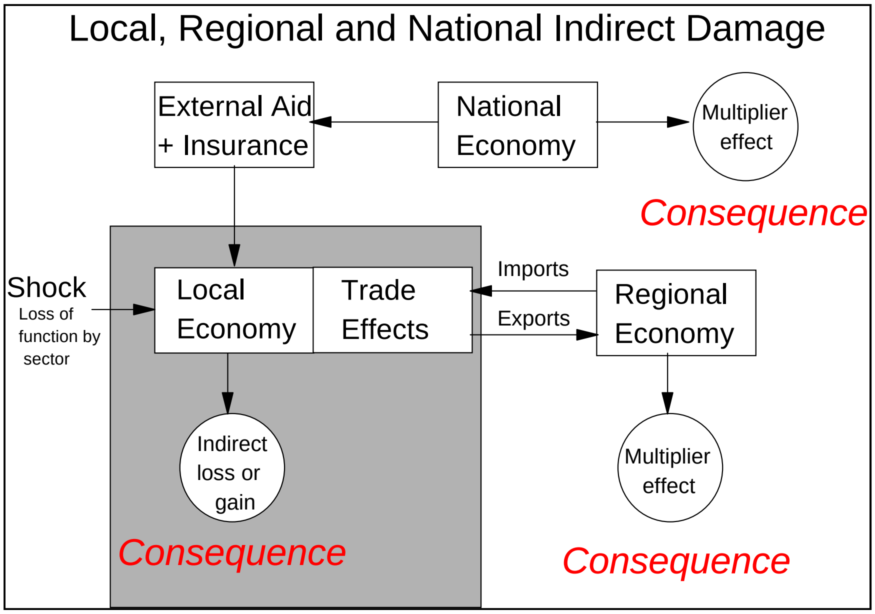

Figure 16.6 Extending the Model to Include Larger Regional and National Losses

16.5.3.2 Alternative Modeling Techniques

It is possible for an economist to use other modeling strategies in conjunction with this loss estimation methodology. For instance, if the region being studied already utilizes a working Computable General Equilibrium model, it could be used to estimate indirect economic loss. Linear Programming methods are also potentially useful. Finally, though not recommended, it is possible to simply feed the direct loss information through a standard set of I-O multipliers (see the discussions in Sections 16.2 and 16.3 above).[10]

16.6 Example Solutions

[10] See, for example, Shoven and Whaley (1992) for general discussion of CGE systems, and Brookshire and McKee (1992) and Boisvert (1995) for applications to earthquakes.

Linear programming offers a simpler alternative to the CGE approach (Cochrane, 1975; Rose et al., 1997). Again, interindustry trade flows form the basis of the model. As in the previous two methods, the A matrix guides the reallocation of production; the output of each sector is comprised of a fixed proportion of other sector outputs. However, unlike the previous methods, an optimizing routine is utilized to search for that production combination that minimizes the extent to which regional income is impacted by the event.

The results derived from I-O, LP and CGE models are likely to vary. Linear programming is likely to provide the most optimistic projection of loss and the Indirect Loss Module the most pessimistic. The reason for this conclusion rests on the high degree of flexibility assumed (in both the CGE and linear programming) in shifting resource use. It is unlikely that production could be redirected without concern for contractual arrangements, or without considering household preferences. The optimization alternative typically ignores both, though this problem can be mitigated somewhat by the inclusion of explicit constraints (see, for example, Rose and Benavides, 1997).

The following examples are provided to both illustrate how a typical indirect loss analysis is performed, and to show the wide range of results possible. Indirect loss patterns (produced from thousands of monte carlo simulations) are then analyzed to derive several general principles relating direct and indirect losses. The resultant patterns and assessments are provided to assist the user in interpreting their own results. First, a simple one-sector supply shock is analyzed to clarify how the model works. The Colorado State Hazards Assessment Laboratory version of the Indirect Loss Module was utilized to perform these analyses. This was done in order to isolate and analyze particular damage patterns. This will create discrepancies between the methodology's output and what is reported by the CSU model.

16.6.1 Simple One-Sector Supply Shock - No Excess Capacity

Table 16.20 shows the final solution for the example discussed above in Section 16.5.1.2, i.e., a 30 percent decline in the functionality of the transportation sector. In this experiment no adjustments were permitted (all percentages are zero except for the supply shock). Table 16.19 shows the initial conditions (output, income and employment) and the adjusted capacities. The mobility of the construction industry shows up as excess capacity. Because reconstruction spending in the example is assumed zero, the capacity goes unutilized. Table 16.20 (right hand side) shows the resultant impact on output, income and employment. The overall percent reduction in these three categories is computed from regional outputs, incomes and employments with and without the event.

In this example of a highly constrained economy, the 30 percent shock to transportation, produces 1.07, 1.46, and a 1.06 percent change in *direct* output, income and employment, respectively. Because of the constraints assumed, total losses (direct and indirect) are approximately 30 times the direct loss (nearly 30 percent).

16.6.2 The Northridge Earthquake

The following scenarios illustrate the sensitivity of indirect loss to the amounts of outside assistance provided and the degree to which the lifelines (particularly transportation) are disrupted. Four scenarios are presented along with the inputs required to run the Indirect Loss Module. Scenario A looks at the twin effects of $26 billion of reconstruction spending, financed internally (i.e., no external aid), and temporary disruption to the transportation system. Scenario B removes reconstruction spending. Scenario C removes the transportation constraint, but eliminates rebuilding. Scenario D removes the transportation constraint, while the $26 billion of rebuilding expenditures is assumed to be financed by a combination of insurance moneys and federal aid.

Table 16.21 shows the IMPLAN transactions matrix for Los Angeles county. Tables 16.23 and 16.24 summarize the inputs used. The results provided in Tables 16.22, 16.25, 16.27 and 16.31 point out several important issues. First, Scenario D comes closest to capturing what did occur. A relatively small proportion of the rebuilding costs were financed internally. As a result, the negative effects of the disruption to transportation were masked by the stimulative effect of rebuilding. The 7.83% net increase in incomes earned in the county are surprisingly close to the observed rise in Los Angeles County taxable sales (7.35%).

Table 16.18 Initial Transactions Matrix

Initial Shock	**0.00**	**0.00**	**0.00**	**0.00**	**30.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**Total**
Total Change	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**Change**
	Ag	**Mine**	**Cnst**	**Mfg**	**Trns**	**Trde**	**FIRE**	**Serv**	**Govt**	**Misc**	**HH**	
Ag	730	0.1	24.6	503.8	2.3	35.1	141.1	34	1.9	0	145.5	0.00%
Mine	1.1	11.6	6.1	12.7	4.2	0.8	0.2	1.6	2.1	0	20.7	0.00%
Cnst	87.5	6	13.8	295.4	248.4	48.1	403.8	313.4	172.6	0	0	0.00%
Mfg	71.6	8.4	384.6	4,791	51.9	178.8	37.3	424.1	7.8	0	1,565	0.00%
Trns	218.3	20.4	261.2	1,468.2	456.7	200.1	126.7	361.3	76.2	0	1,624	0.00%
Trde	99.8	4.1	461.8	994.1	44.2	78.7	27.2	214	12.8	0	8,477	0.00%
FIRE	195.3	24.5	85.4	279.4	91.5	228.4	1,132	702.1	13	0	10,005	0.00%
Serv	93.4	12.7	552.5	789.5	171.3	294.6	300.6	1,032	19.3	0	10,147	0.00%
								.1				
Govt	28.6	6	22.8	313.5	36.8	78.3	71.3	169.7	29	0	582	0.00%
Misc	0	0	0	0	0	0	0	0	0	0	0	0.00%
HH	1,879	195	3,704	12,729	2,266.3	7,305	2,108	9,724	6,567	0	0	0.00%
											Sum	0.00%

Table 16.19 Original Conditions and Adjustments

	Original Conditions			Additional Demands			Additional Supplies		
Sector	**Output**	**HH Payments**	**Employ.**	**Inventory Buildup Capability**	**Export Capability**	**Desired New Final Demand**	**Potential Output Increase**	**Potential Imports**	**Potential Inventory Drawdown**
Ag	5,964	1,879	106,253	0	0	0	0	0	0
Mine	1,092	195	4,739	0	0	0	0	0	0
Cnst	10,984	3,704	144,407	0	0	0	10,040	0	0
Mfg	52,811	12,729	378,400	0	0	0	0	0	0
Trns	7,169	2,266	72,169	0	0	0	0	0	0
Trde	13,484	7,306	451,276	0	0	0	0	0	0
FIRE	15,791	2,108	124,514	0	0	0	0	0	0
Serv	19,065	9,724	492,969	0	0	0	0	0	0
Govt	7,550	6,567	266,107	0	0	0	0	0	0
Misc	0	0	0	0	0	0	0	0	0
HH									
Totals	66,312	46,478	2,040,834						

Table 16.20 Final Conditions

		Post- Event Spending		Final Losses					
Sector	**Net Change Next Round**	**Hhld Spending**	**Exports**	**Post-Event Final Output**	**Final Output Direct Loss Only**	**Post-Event Hhld Payments**	**Hhld Payments Direct Loss Only**	**Post-Event Employ.**	**Employ. Direct Loss Only**
Ag	29.98%	102	1,284	4,176	5,964	1,316	1,879	74,398	106,253
Mine	29.98%	15	285	765	1,092	137	195	3,318	4,739
Cnst	29.98%	0	252	7,691	10,984	2,594	3,704	101,113	144,407
Mfg	29.98%	1,096	12,565	36,978	52,811	8,914	12,729	264,955	378,400
Trns	30.00%	1,137	617	5,018	5,018	1,586	1,586	50,518	50,518
Trde	29.98%	5,936	801	9,442	13,484	5,116	7,306	315,982	451,276
FIRE	29.98%	7,005	865	11,057	15,791	1,476	2,108	87,184	124,514
Serv	29.98%	7,105	1,608	13,349	19,065	6,809	9,724	345,175	492,969
Govt	29.98%	408	97	5,287	7,550	4,599	6,567	186,327	266,107
Misc	0.00%	0	0	0	0	0	0	0	0
HH									
Totals		22,802	18,375	140,194	198,072	32,544	45,798	1,428,970	2,019,183
Total % Change	29.98%	-29.98%	-29.98%	-29.98%	-1.07%	-29.98%	-1.46%	-29.98%	-1.06%

Second, the effects of transportation bottlenecks alone can only be observed by stripping away rebuilding expenditures, Scenario B. Here we can see that income would have fallen, not risen. The disaster would have caused another $10 billion in indirect losses. Third, outside assistance is an important element in the recovery process. The effects of internal financing are shown in Scenario A. Here, an additional $1.5 billion in income losses would have been observed had the victims been forced to borrow to rebuild.

These scenarios underscore the importance of rebuilding on the impacted region's post-disaster economic performance. This is particularly true when insurance and federal assistance is made available. Another important lesson learned from these experiments is that case studies of indirect loss can produce misleading results. Clearly Northridge and Los Angeles County did not benefit from disruptions to its transportation network. Yet, an analysis of post-disaster spending and incomes (taxable sales reported after the earthquake) tends to indicate such had occurred. As just shown the Indirect Loss Module is capable of separating the stimulative effects of rebuilding from the "true" indirect losses produced as a result of forward and backward linked damages.

Table 16.21 Los Angeles County Transactions Matrix

	Ag	**Mine**	**Cnst**	**Mfg**	**Trns**	**Trde**	**FIRE**	**Serv**	**Govt**	**Misc**	**HH**
Ag	26	0	28	173	2	13	213	46	5	0	49
Mine	2	1	13	66	44	16	2	22	53	0	119
Cnst	14	10	24	353	482	167	1162	694	603	0	0
Mfg	121	25	1942	13201	1363	1707	378	3415	285	0	12219
Trns	50	38	929	4069	2381	1724	920	2741	1078	0	6677
Trde	43	6	1609	2662	207	511	140	904	103	0	21900
FIRE	60	189	301	1080	653	1519	7279	4210	134	0	28696
Serv	122	37	2839	4933	1916	4636	3177	14326	275	0	31357
Govt	17	25	96	1195	200	651	389	1213	255	0	2514
Misc	0	0	0	0	0	0	0	0	0	0	0
HH	660	424	8846	30473	8601	25129	10985	51410	17318	0	0
TypeII sum	1115	754	16627	58204	15850	36072	24645	78981	20111	0	103530
TypeII FP	431	4936	7708	62601	10039	13605	32460	13019	1838	0	57838
Imports	403	1201	6920	42925	3400	3284	1744	6543	669	0	0
Ind Out	1546	5690	24335	120805	25888	49677	57105	92000	21948	0	161368

Table 16.22 Results – Scenario A
Constrained Transportation Sector
Reconstruction

Direct Output Loss	($15,508)	-2.77%
Indirect Output Loss	$8,286	1.48%
Total Loss (Direct+Indirect)	($7,222)	-1.29%
Direct Income Loss	($3,710)	-2.41%
Indirect Income Loss	$1,552	1.01%
Total Loss Income (Direct+Indirect)	($2,158)	-1.40%
Direct Employment Loss	(122,015)	-2.39%
Indirect Employment Loss	24,013	0.47%
Total Employment Loss (Direct+Indirect)	(98,002)	-1.92%

Table 16.23 Scenario A; Damage and User Inputs

Economic Sector	Percent Damage
Agriculture	0.00%
Mining	0.00%
Construction	0.00%
Manufacturing	3.80%
Transportation	10.00%
Trade	3.50%
Finance, Insurance and Real Estate	2.00%
Service	0.86%
Government	0.87%
Misc.	0.00%

Assumptions	Value
Rate of Unemployment	8.00%
Excess Capacity in Transportation	0.00%
Earthquake Construction Spending	$26 billion

Table 16.24 Restoration and Reconstruction Spending after Northridge

Sector	Months after the Northridge Earthquake										
	1	**2**	**3**	**6**	**9**	**12**	**24**	**36**	**48**	**60**	**120**
Agriculture	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Mining	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Construction	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Manufacturing	3.80	3.19	2.58	1.98	1.37	0.76	0.15	0.00	0.00	0.00	0.00
Transportation	10.00	8.40	6.80	5.20	3.60	2.00	0.40	0.00	0.00	0.00	0.00
Trade	3.50	2.94	2.38	1.82	1.26	0.70	0.14	0.00	0.00	0.00	0.00
FIRE	2.00	1.68	1.36	1.04	0.72	0.40	0.08	0.00	0.00	0.00	0.00
Service	0.86	0.72	0.58	0.45	0.31	0.17	0.03	0.00	0.00	0.00	0.00
Government	0.87	0.73	0.59	0.45	0.31	0.17	0.03	0.00	0.00	0.00	0.00
Misc.	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Spending/Month	Months after the Northridge Earthquake										
	1	**2**	**3**	**6**	**9**	**12**	**24**	**36**	**48**	**60**	**120**
$ Billons	0.10	0.30	0.60	0.70	0.70	0.60	0.30	0.12	0.00	0.00	0.00

**Table 16.25 Results – Scenario B
Constrained Transportation Sector
No Reconstruction**

Direct Output Loss	($15,508)	-2.77%
Indirect Output Loss	($33,685)	-6.01%
Total Loss (Direct+Indirect)	($49,193)	-8.78%
Direct Income Loss	($3,710)	-2.41%
Indirect Income Loss	($9,692)	-6.30%
Total Loss Income (Direct+Indirect)	($13,403)	-8.71%
Direct Employment Loss	(122,015)	-2.39%
Indirect Employment Loss	(318,930)	-6.24%
Total Employment Loss (Direct+Indirect)	(440,945)	-8.63%

Table 16.26 Scenario B, User Inputs

Assumptions	Value
Rate of Unemployment	8.0%
Excess Capacity in Transportation	0.00%
Earthquake Construction Spending	$0 billion

**Table 16.27 Results – Scenario C
Unconstrained Transportation Sector
No Reconstruction**

Direct Output Loss	($15,508)	-2.77%
Indirect Output Loss	$2,648	0.47%
Total Loss (Direct+Indirect)	($12,860)	-2.29%
Direct Income Loss	($3,710)	-2.41%
Indirect Income Loss	$640	0.42%
Total Loss Income (Direct+Indirect)	($3,070)	-2.00%
Direct Employment Loss	(122,015)	-2.39%
Indirect Employment Loss	21,250	0.42%
Total Employment Loss (Direct+Indirect)	(100,765)	-1.97%

Table 16.28 Scenario C, User Inputs

Assumptions	Value
Rate of Unemployment	8.00%
Excess Capacity in Transportation	no constraint
Earthquake Construction Spending	$0 billion

**Table 16.29 Results – Scenario D
Unconstrained Transportation Sector
Reconstruction, No Indebtedness**

Direct Output Loss	($9,754)	-2.12%
Indirect Output Loss	$37,061	8.05%
Total Loss (Direct+Indirect)	$27,307	5.93%
Direct Income Loss	($2,850)	-1.85%
Indirect Income Loss	$12,046	7.83%
Total Loss Income (Direct+Indirect)	$9,196	5.98%
Direct Employment Loss	(99,044)	-1.94%
Indirect Employment Loss	370,072	7.24%
Total Employment Loss (Direct+Indirect)	271,028	5.31%

Table 16.30 Scenario D, User Inputs

Assumptions	Value
Rate of Unemployment	8.00%
Excess Capacity in Transportation	no constraint
Earthquake Construction Spending	$26 billion

16.6.3 The Sensitivity of Indirect Loss to Capacity, Damage and Reconstruction

Our analysis to date suggests that there may not be a simple relationship between direct and indirect losses. Much depends upon the pattern of damage, which sectors sustain the greatest disruption, and their relative importance in the economy. In addition, the demand stimulus inherent in the rebuilding process would lessen indirect loss, possibly producing gains in instances where large amounts of excess capacity exist. The sensitivity of indirect loss to random patterns of damage and rebuilding was determined through a series of experiments that are presented in summary form below. Four major classes of experiments were conducted; they are identified and explained in Table 16.31.

Table 16.31 Monte Carlo Experiments

Experiment	Explanation
Damage Pattern	1. Random damage pattern drawn from a uniform probability distribution (all sectors). 2. Random damage pattern drawn from a skewed probability distribution (all sectors). 3. Random pattern of damage to the lifelines sector, no damage to all other sectors.
Outside Assistance	4. Random amounts of rebuilding. 5. Rebuilding in proportion to direct losses

Economic Structure	Different transactions matrices were utilized to evaluate the extent to which economic structure impacted indirect loss when the economy was fully constrained
Internal and External Capacity	The effects of eliminating supplemental imports and exports and varying internal capacity.

Indirect and direct losses were recorded for twenty thousand experiments[11]. The joint density function of direct and indirect loss, along with the probability density function of indirect loss were then plotted to derive relationships capable of being generalized. See Figure 16.7. The joint density function is displayed on the higher of the two horizontal plains. Regions of indirect gain and loss are identified. The lower of the two planes is a contour map (projection) of the joint probability of indirect and direct loss. The back projection is the indirect loss probability density function.

The results of the experiments are plotted in Figures 16.8 through 16.17. As shown, either regional indirect loss or gain can be observed. Which occurs depends upon the combination of the damage pattern, preexisting economic conditions and the amount of outside assistance received. Several of the maps have ready explanations. The map shown in Figure 16.8 is based on two assumptions: 1) the existence of sufficient (to avoid shortages) excess capacity and 2) rebuilding expenditures are proportionate to direct loss. The first assumption eliminates all constraints and, therefore, indirect losses are eliminated as well. By linking reconstruction spending to direct loss, indirect gain (the effect of the construction multiplier) is made proportionate to direct loss. It will be shown below that the slope implied by the contour is a function of the construction multiplier.

It appears from these experiments that reconstruction spending exerts a powerful influence on indirect loss. Figure 16.9 shows the results of an experiment where internal capacity was varied randomly from zero to 30 percent, the shocks were drawn randomly from a uniform probability distribution, and reconstruction spending was random. As shown, indirect losses were recorded for fewer than 10 percent of the cases. Figure 16.10 shows the effect of eliminating reconstruction expenditures. As expected, the gains shown in Figure 16.8 disappear.

[6]Damage to each of 10 economic sectors was determined by generating a random number between zero and one for the uniform distribution and cubing the random number to arrive at a skewed distribution.

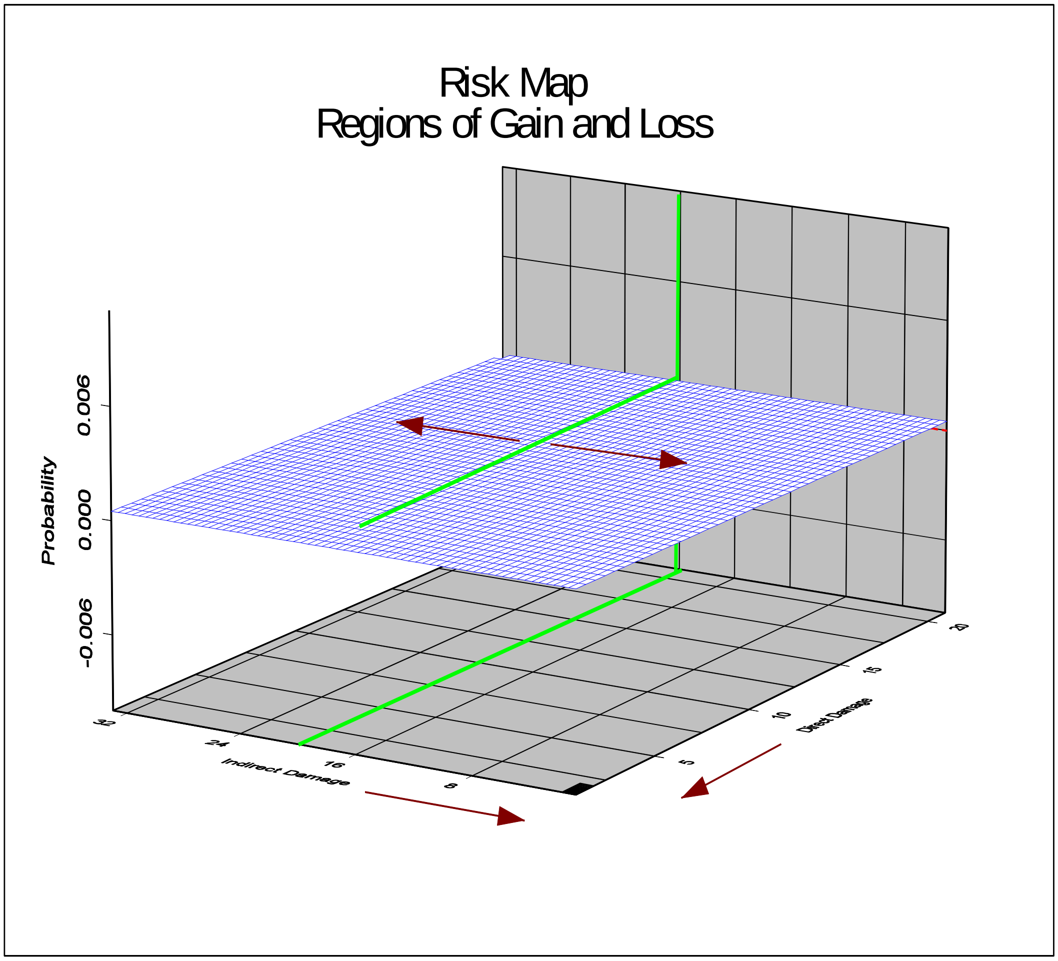

Figure 16.7 Risk Map - Direct vs. Indirect

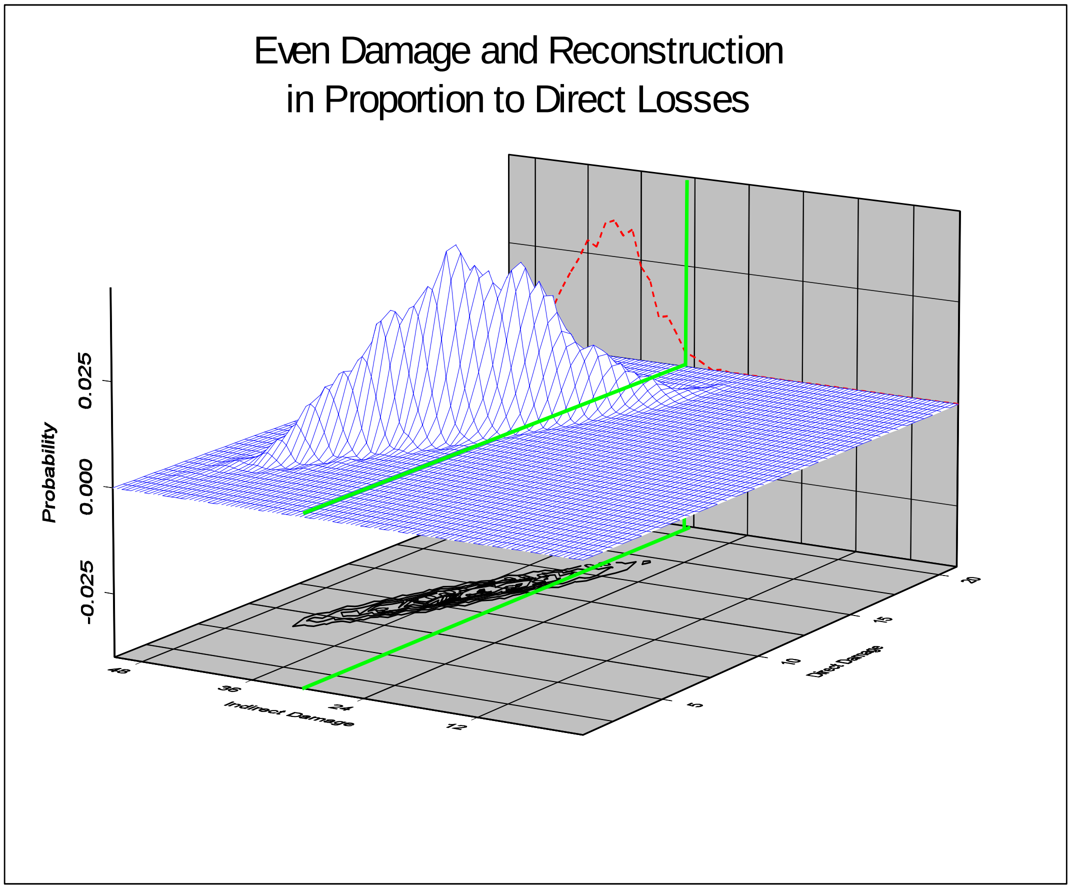

Figure 16.8 Risk Map - No Constraints

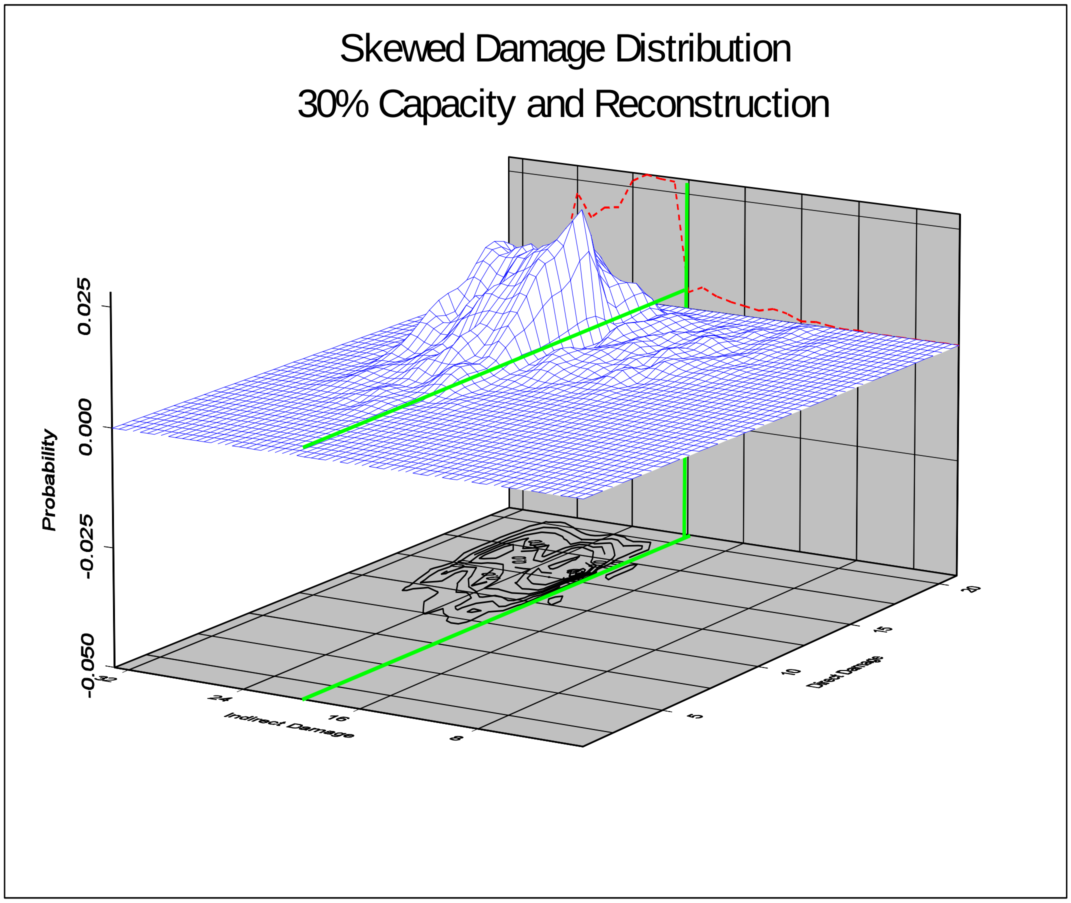

Figure 16.9   Risk Map - Random Capacity

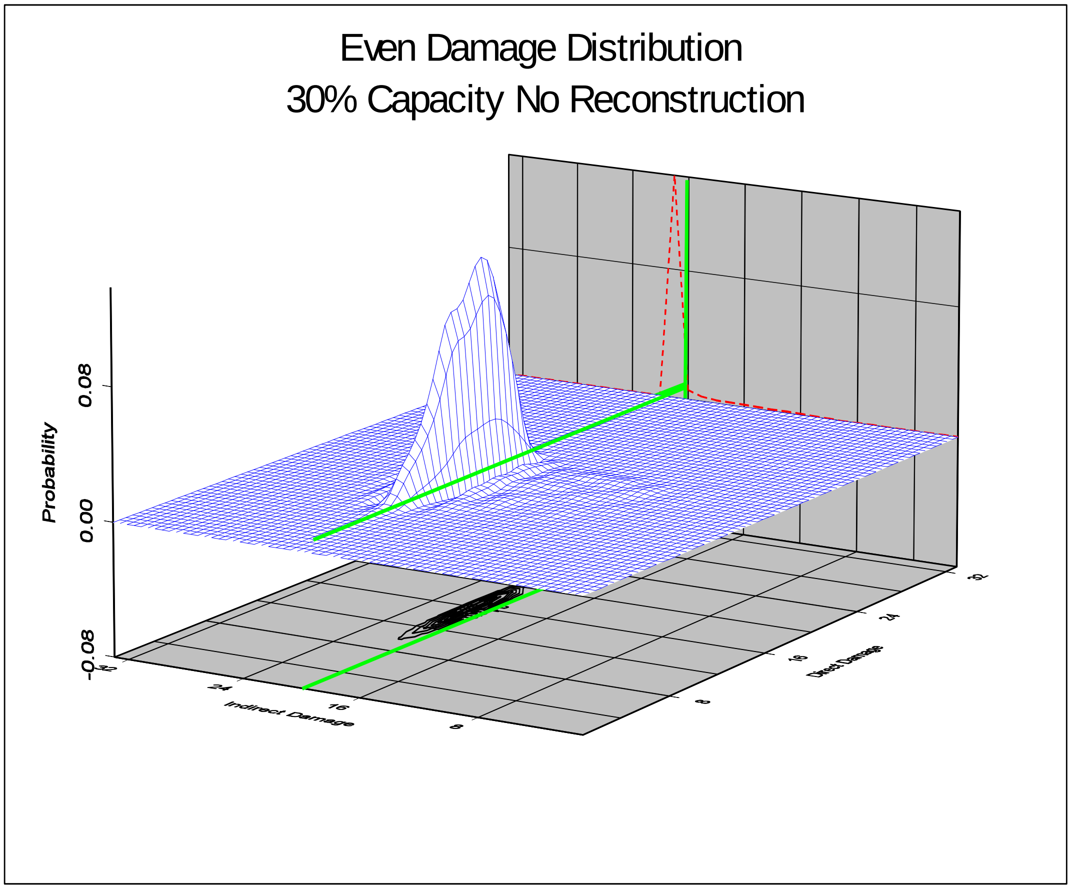

Figure 16.10 Risk Map - No Rebuilding

In contrast, Figure 16.11 shows that when the economy is constrained (internally and externally) indirect losses can be quite high and indirect gains are impossible. The shape of this result map can be explained. The outline of the contour map provided in Figure 16.11 and several regions of the solution set are identified in Figure 16.12. The triangular shape of the map follows directly from the way in which the economy responds to damages. Point B, the uppermost level of indirect loss, results from a maximum shock to the smallest sector. Even though B proved to be improbable, other combinations of low direct loss and relatively high indirect loss were observed. The Line segment D-C shows the effect of a uniform[12] damage patterns. An even pattern of damages produce no indirect loss since the economy remains balanced. Only an uneven pattern of damage produces bottleneck effects and indirect losses. The line segment A-C can be interpreted as the indirect loss frontier. At the extreme, when direct loss is total, indirect loss must be zero. Similarly, when direct loss is total for the smallest sector, indirect loss is maximum. Hence, point A would be observed if the size of the smallest sector

[12]Uniform means that each sector suffers an equal ratio of damage.

approached zero. Line segment D-B shows the influence of increased variance in the pattern of loss. The variance is zero at D and maximum at B.

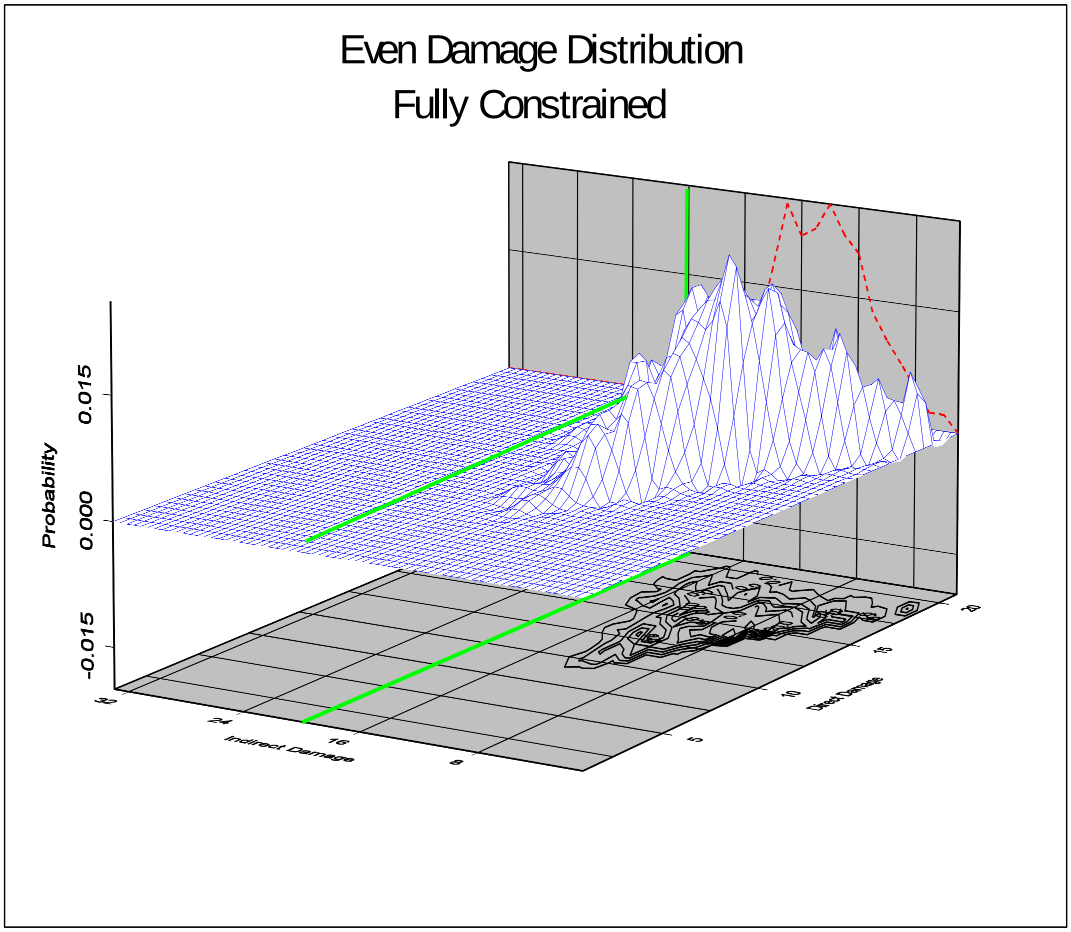

Figure 16.11 Risk Map Fully Constrained

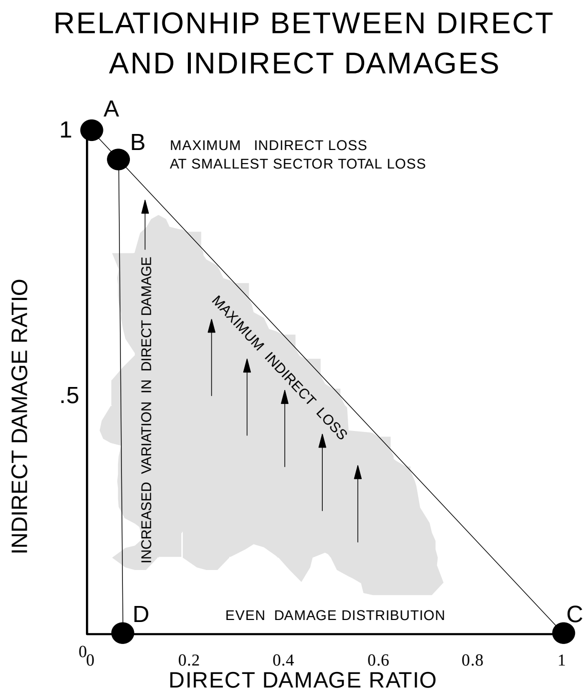

Figure 16.12 Relationship Between Direct and Indirect Damages

Figures 16.13 and 16.14 show the effect of a shock to lifelines (transportation) alone. The only difference between the two experiments is the amount of excess capacity assumed, 30 percent in the former and none in the latter. It is not surprising that this latter scenario produces the potential for sizable indirect losses.

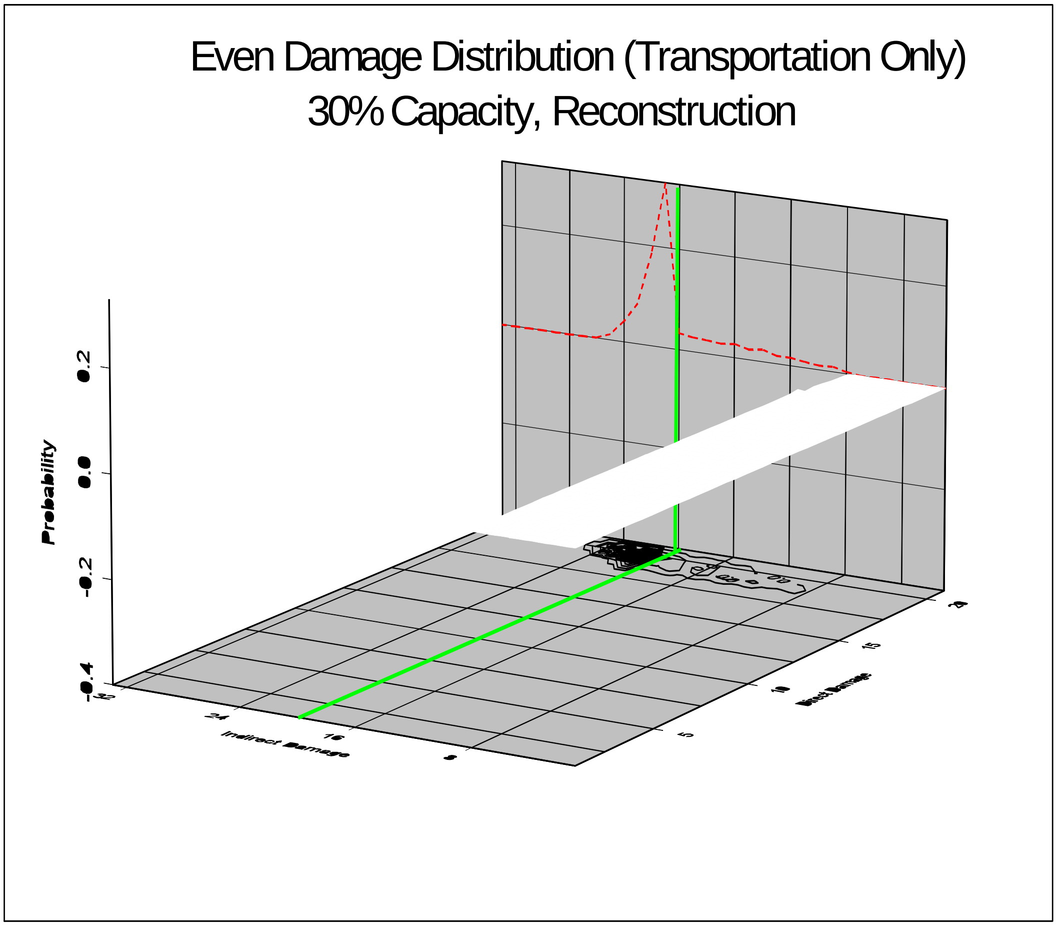

Figure 16.13 Risk Map - Transportation Disruption and Excess Capacity

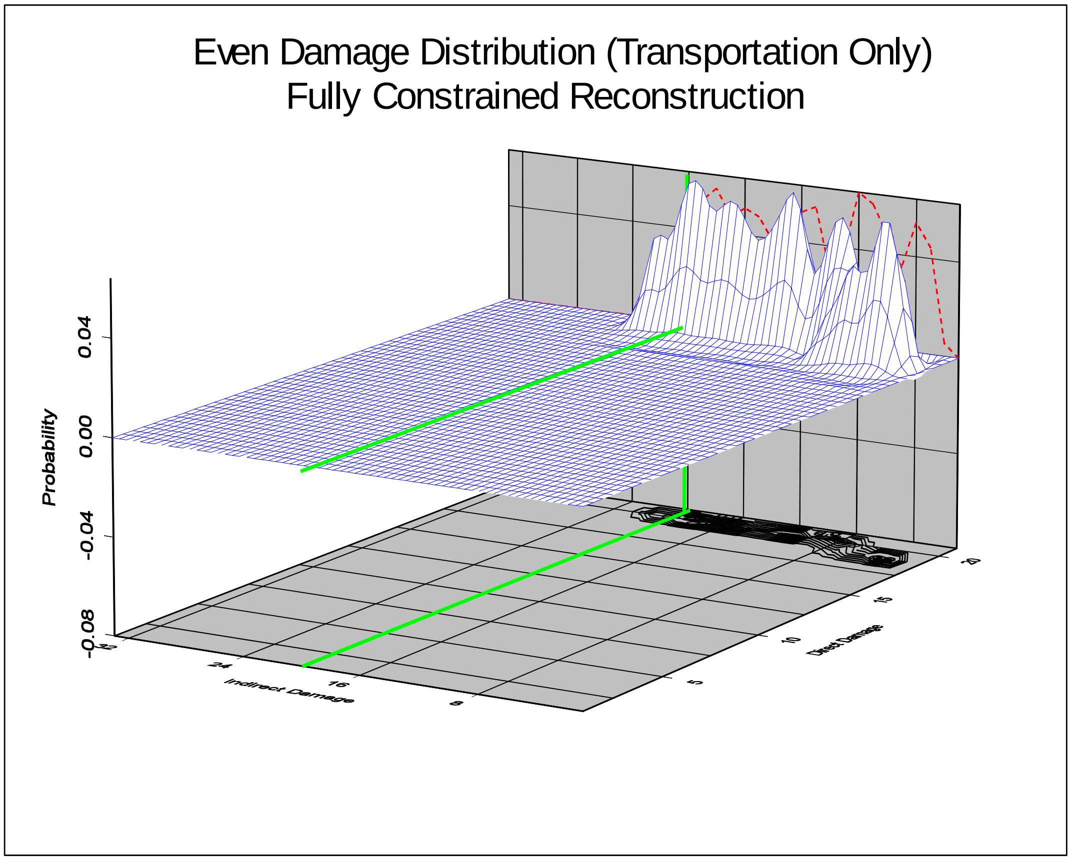

Figure 16.14 Risk Map - Transportation Disruption and No Excess Capacity

Figures 16.15, 16.16 and 16.17 provide a comparison of how economies respond to differing damage patterns, capacities and economic structure. Figure 16.15 summarizes the experiments that varied capacity. Figure 16.16 contrasts the degree of skewness in sectoral damage. As shown, the greater the concentration of damage, the greater the indirect loss as a proportion of total loss. The greater the capacity the greater the chances of indirect gain. Rebuilding expenditures enhances such gains. It is somewhat surprising in Figure 16.17 that economic structure appears to play an insignificant role in determining indirect losses when the economy is fully constrained. All three economies shown appear to produce very similar joint density functions. Clearly, the same conclusion will not apply in the event that internal excess capacity exists. In that case, economic gains are sensitive to economic structure, through a construction multiplier.

It was asserted above that, if unconstrained, this model produces a solution that is equivalent to what conventional input-output techniques yield. This is easily demonstrated by making reconstruction expenditures proportionate to direct loss. A simple linear regression of spending and indirect gain should produce a slope (zero intercept) equal to the construction multiplier. Figure 16.18 shows the result of this experiment. The slopes of the indirect gain functions for Los Angeles and Santa Cruz are

1.397 and 1.145 respectively. The respective IMPLAN construction multipliers for these two counties are 1.431 and 1.141.

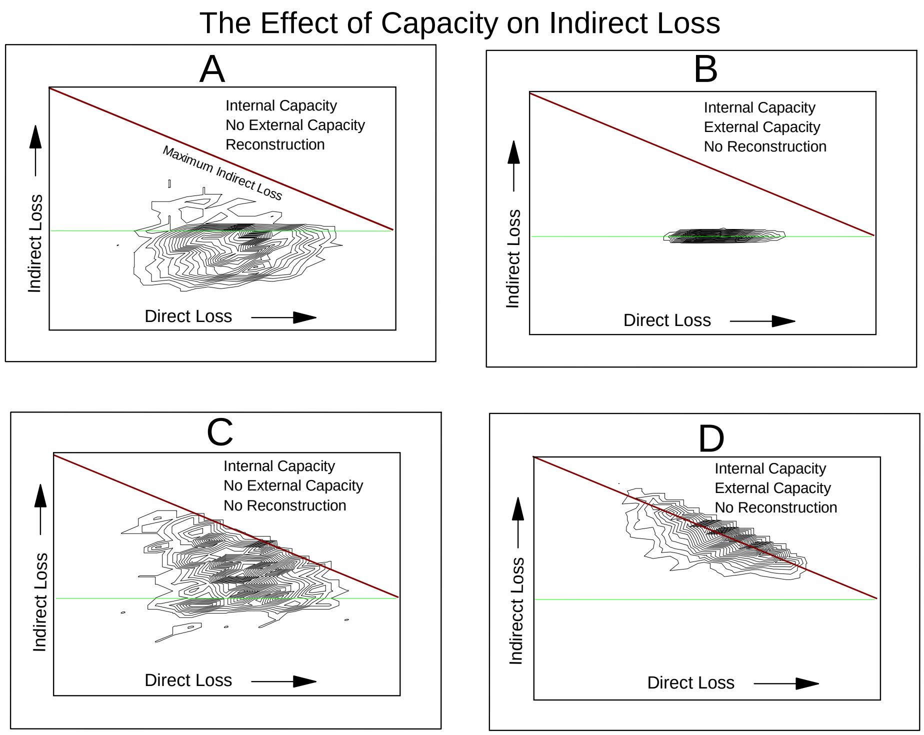

Figure 16.15 Risk Maps—The Effects of Capacity

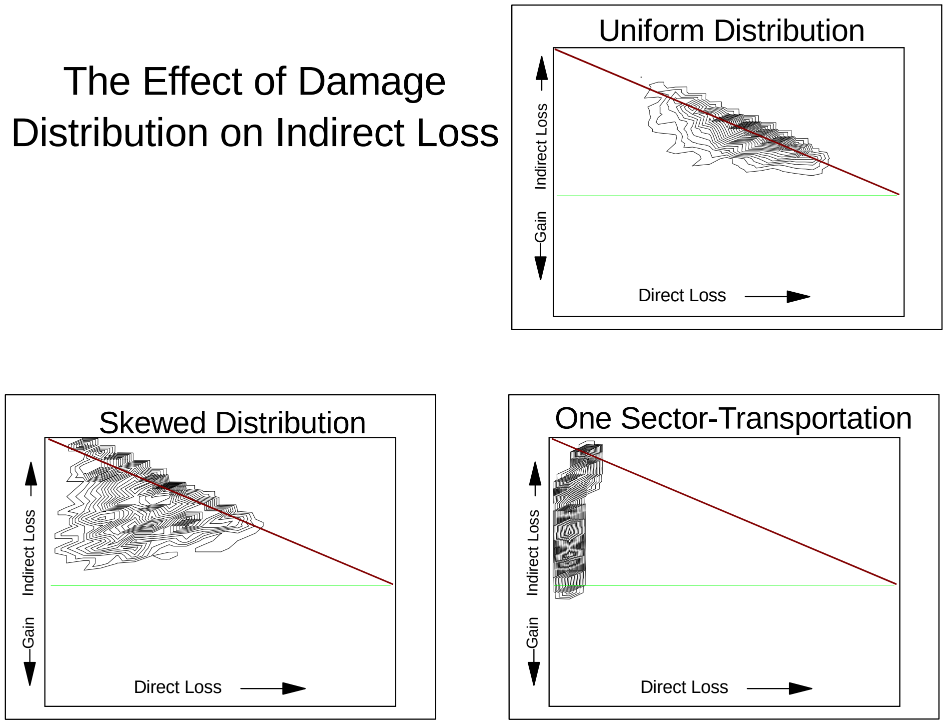

Figure 16.16 Risk Maps – The Effects of Damage Distributions

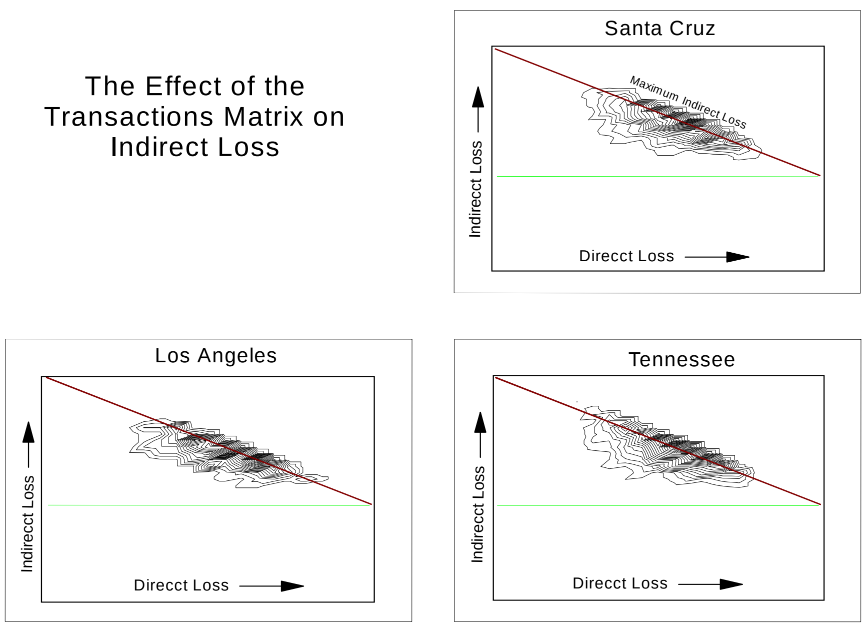

Figure 16.17 Risk Map -- The Effect of the Transactions Matrix When Fully Constrained

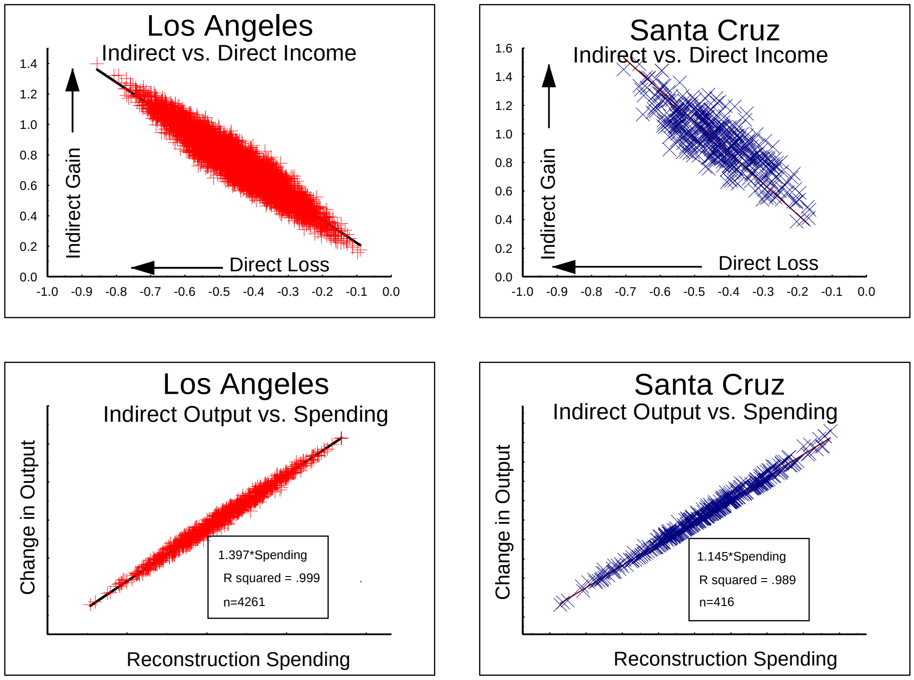

Figure 16.18 Indirect Gains and the Construction Multiplier

16.6.4 Observations About Indirect Loss

The following generalizations can be drawn from the foregoing experiments:

1. Holding capacity and rebuilding fixed, indirect losses are inversely proportional to the size of the sector shocked. For example, in the extreme case of an economy with a dominant sector, the rest of the economy in which indirect effects take place is relatively small.

2. Imports can either reduce or promote indirect loss, dampening losses if used to supply industry with raw and semi-finished ingredients so that production can be resumed, and accentuating losses if imports are used to satisfy unmet household demand, thus displacing local production.

3. Shocks to a fully constrained economy produce indirect losses, but not indirect gains because there is no leeway for the latter (e.g., multiplier effects from construction). In such an economy, the probability of indirect losses exceeding direct damage is approximately 50 percent.

4. The greater the variance in the pattern of damage, the greater the indirect loss due to factors such as "bottleneck" effects.

5. A uniform pattern of loss produces no indirect loss because internal rearrangements of buyers and sellers can be perfectly matched (barring transportation problems and contractual constraints).

6. If the economy is fully constrained, indirect losses are maximum when the economy's smallest sector is totally destroyed (this is the inverse of generalization No. 1).

7. When unconstrained, the economy expands from the construction stimulus as conventional I-O techniques (multipliers) would predict.

8. A dynamic analysis of indirect loss reflects both the forward and backward linked losses and future demand changes resulting from disaster caused indebtedness, both of which are generally long-run dampening effects.

9. When economies are fully constrained, indirect loss appears to be insensitive to economic structure. Different transactions matrices yield marginally different indirect losses, most likely because of similarities of multiplier values or stochastic offsets of multipliers of differing values.

10. From a regional accounting stance reconstruction gains tend to dominate indirect losses when excess capacity exists.

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Appendix 16A

Default Data Analysis
Synthetic Economies

113 state and county IMPLAN tables were analyzed to derive synthetic transactions matrices for the Default Data Analysis model. A frequency histogram of employment (See Tables 16A.2 through 16A.4) revealed that 90 percent of the tables could be classified as Manufacturing/Service, Service/Manufacturing, or Service/Trade. Since nearly two thirds of employment in these tables can be traced to these three sectors, it was decided that this means of classifying economies could be used as a basis for deriving Default Data Analysis interindustry trade flows. Further adjustments were made to reflect the size of the economy. Four size classes were created resulting in the 12 way classification shown below.

Table 16A.1 Classification of Synthetic Economies

Employment		Type		
Upper Bound	**Lower Bound**	**Manufacturing/ Service**	**Service/ Manufacturing**	**Service/ Trade**
unlimited	2 million	SUP1	SUP2	SUP3
2 million	.6 million	LAR1	LAR2	LAR3
.6 million	30,000	MID1	MID2	MID3
30,000	0	LOW1	LOW2	LOW3

The particular states and counties which were utilized to create the 12 synthetic tables are shown in Tables 16A.5 through 16A.6.

Table 16A.2 Manufacturing/Service

Sector	**0**	**10**	**20**	**30**	**40**	**50**	**60**	**70**	**80**	**90**	**100**	**AVG**
Manufacturing	0	0	0	9	25	10	4	1	0	0	0	37.5%
Government	0	0	14	35	0	0	0	0	0	0	0	21.5%
FIRE	0	3	44	2	0	0	0	0	0	0	0	13.6%
Trade	0	42	7	0	0	0	0	0	0	0	0	7.5%
Service	0	46	3	0	0	0	0	0	0	0	0	6.3%
Construction	0	46	3	0	0	0	0	0	0	0	0	6.3%
Transportation	0	48	1	0	0	0	0	0	0	0	0	6.1%
Agriculture	0	49	0	0	0	0	0	0	0	0	0	0.6%
Mining	0	49	0	0	0	0	0	0	0	0	0	0.6%

Table 16A.3 Service/Manufacturing

Sector	0	10	20	30	40	50	60	70	80	90	100	AVG
Government	0	0	1	20	11	1	0	0	0	0	0	28.6%
Manufacturing	0	0	12	18	2	0	1	0	0	0	0	23.4%
FIRE	0	2	29	2	0	0	0	0	0	0	0	13.9%
Trade	0	27	6	0	0	0	0	0	0	0	0	8.4%
Transportation	0	25	8	0	0	0	0	0	0	0	0	8.3%
Service	0	28	5	0	0	0	0	0	0	0	0	7.8%
Construction	0	28	5	0	0	0	0	0	0	0	0	7.1%
Mining	0	32	1	0	0	0	0	0	0	0	0	2.2%
Agriculture	0	33	0	0	0	0	0	0	0	0	0	0.4%

Table 16A.4 Service/Trade

Sector	0	10	20	30	40	50	60	70	80	90	100	AVG
Government	0	0	0	2	7	6	0	1	0	0	0	37.4%
Service	0	1	8	7	0	0	0	0	0	0	0	18.2%
Transportation	0	10	6	0	0	0	0	0	0	0	0	9.3%
Manufacturing	0	9	7	0	0	0	0	0	0	0	0	9.2%
Construction	0	13	3	0	0	0	0	0	0	0	0	7.8%
FIRE	0	13	3	0	0	0	0	0	0	0	0	7.4%
Trade	0	14	2	0	0	0	0	0	0	0	0	6.0%
Mining	0	13	2	1	0	0	0	0	0	0	0	4.1%
Agriculture	0	16	0	0	0	0	0	0	0	0	0	0.5%

Table 16A.5 Manufacturing/Service Economy

Super			Large		
FIPS	**STATE/CNTY.**	**EMPLOY.**	**FIPS**	**STATE/CNTY.**	**EMPLOY.**
39,000	Ohio	5,831,755	53,033	King, WA	1,112,072
26,000	Michigan	4,714,837	9,000	Connecticut	1,989,824
13,000	Georgia	3,673,183	19,000	Iowa	1,635,164
37,000	North Carolina	3,858,712	5,000	Arkansas	1,194,095
18,000	Indiana	3,064,277	28,000	Mississippi	1,186,175
29,000	Missouri	2,986,395	33,000	New Hampshire	655,638
53,000	Washington	2,777,829	6,059	Orange, CA	1,514,438
27,000	Minnesota	2,642,082	41,000	Oregon	1,621,333
47,000	Tennessee	2,733,161	23,000	Maine	709,529
55,000	Wisconsin	2,796,572			
1,000	Alabama	2,028,495			

Mid			Low		
FIPS	**STATE/CNTY.**	**EMPLOY.**	**FIPS**	**STATE/CNTY.**	**EMPLOY.**
8,059	Jefferson, CO	224,465	48,257	Kaufman, TX	19,758
53,061	Snohomish, WA	212,107	6,069	San Benito, CA	16,274
41,067	Washington, OR	179,331	55,029	Door, WI	15,682
55,009	Brown, WI	123,090	55,093	Pierce, WI	13,707
41,005	Clackamas, OR	129,712	55,099	Price, WI	8,637
55,087	Outagamie, WI	89,502	8,087	Morgan, CO	12,408
48,121	Denton, TX	88,726	41,015	Curry, OR	8,996
49,057	Weber, UT	77,041	48,285	Lavaca, TX	9,272
55,089	Ozaukee, WI	36,021	55,129	Washburn, WI	6,590
48,139	Ellis, TX	31,798	41,035	Klamath, OR	28,783
41,071	Yamhill, OR	30,416	55,109	St.Croix, WI	23,213
16,000	Idaho	547,056			
50,000	Vermont	345,166			
44,000	Rhode Island	554,121			
10,000	Delaware	414,343			

Table 16A.6 Service/Manufacturing Economy

Super			Large		
FIPS	STATE/CNTY.	EMPLOY.	FIPS	STATE/CNTY.	EMPLOY.
36,000	New York	9,747,535	19,000	Iowa	1,635,164
6,037	Los Angeles, CA	5,108,213	40,000	Oklahoma	1,614,109
48,000	Texas	8,900,073	4,013	Maricopa, AZ	1,212,392
34,000	New Jersey	4,327,815	22,000	Louisiana	1,969,967
25,000	Massachusetts	3,644,604	5,000	Arkansas	1,194,095
6,000	California	16,532,145	31,000	Nebraska	987,260
13,000	Georgia	3,673,183	54,000	West Virginia	769,662
51,000	Virginia	3,695,334	4,000	Arizona	1,870,344
24,000	Maryland	2,697,448	20,000	Kansas	1,485,215
8,000	Colorado	2,017,818	49,000	Utah	895,454

Mid			Low		
FIPS	STATE/CNTY.	EMPLOY.	FIPS	STATE/CNTY.	EMPLOY.
35,001	Bernalillo, NM	306,176	35,041	Roosevelt, NM	7,593
53,053	Pierce, WA	263,512			
41,051	Multnomah, OR	441,788			
53,063	Spokane, WA	192,662			
48,085	Collin, TX	103,086			
6,089	Shasta, CA	71,398			
48,485	Wichita, TX	74,491			
49,011	Davis, UT	78,170			
6,071	San Bernardino, CA	529,198			
49,035	Salt Lake, UT	436,832			
6,065	Riverside, CA	434,846			
6,111	Ventura, CA	313,911			

Table 16A.7 Service/Trade Economy

Super			Large		
FIPS	STATE/CNTY.	EMPLOY.	FIPS	STATE/CNTY.	EMPLOY.
	NONE		11,000	District of Columbia	761,680
			32,000	Nevada	741,574
			15,000	Hawaii	696,759
			35,000	New Mexico	745,539

Mid			Low		
FIPS	STATE/CNTY.	EMPLOY.	FIPS	STATE/CNTY.	EMPLOY.
30,000	Montana	433,623	48,397	Rockwall, TX	9,140
8,005	Arapahoe, CO	217,208	8,067	La Plata, CO	19,079
4,003	Cochise, AZ	39,611	56,001	Albany, WY	16,959
38,000	North Dakota	377,987	56,041	Uinta, WY	9,948
6,029	Kern, CA	262,422	55,125	Vilas, WI	8,364
56,021	Laramie, WY	44,438	35,061	Valencia, NM	11,787

Chapter 17
Annualized Losses

The U.S. Geological Survey (USGS) provided the probabilistic seismic hazard data for the entire United States. A three-step process was used to convert the data into a Hazus compatible format.

Step 1: Compute the PGA, SA@0.3 and SA@1.0 at each grid point for the eight return periods.

The USGS provided the hazard data as a set of 18 (or 20) intensity-probability pairs for each of the approximately 150,000 grid points used to cover the United States. For each grid point, a linear interpolation of the data was used to calculate the ground motion values corresponding to each of the eight return periods used in this study (100, 250, 500, 750, 1000, 1500, 2000, and 2500 years).

Table 17-1 below shows an example of USGS hazard data for an individual grid point.

Table 17-1. Example of the USGS Hazard Data

#	Ground Motion Data					
	PGA	AFE	SA (0.3 sec)	AFE	SA (1.0 sec)	AFE
1	5.00E-03	2.49E-02	5.00E-03	3.28E-02	2.50E-03	2.85E-02
2	7.00E-03	2.07E-02	7.50E-03	2.89E-02	3.75E-03	2.37E-02
3	9.80E-03	1.65E-02	1.13E-02	2.40E-02	5.63E-03	1.84E-02
4	1.37E-02	1.25E-02	1.69E-02	1.85E-02	8.44E-03	1.34E-02
5	1.92E-02	8.76E-03	2.53E-02	1.30E-02	1.27E-02	9.24E-03
6	2.69E-02	5.86E-03	3.80E-02	8.45E-03	1.90E-02	6.25E-03
7	3.76E-02	3.87E-03	5.70E-02	5.29E-03	2.85E-02	4.23E-03
8	5.27E-02	2.64E-03	8.54E-02	3.36E-03	4.27E-02	2.95E-03
9	7.38E-02	1.90E-03	1.28E-01	2.27E-03	6.41E-02	2.14E-03
10	1.03E-01	1.43E-03	1.92E-01	1.63E-03	9.61E-02	1.60E-03
11	1.45E-01	1.08E-03	2.88E-01	1.19E-03	1.44E-01	1.18E-03
12	2.03E-01	7.73E-04	4.32E-01	8.28E-04	2.16E-01	8.08E-04
13	2.84E-01	5.06E-04	6.49E-01	5.03E-04	3.24E-01	4.83E-04
14	3.97E-01	2.88E-04	1.30E+00	1.30E-04	4.87E-01	2.36E-04
15	5.56E-01	1.35E-04	1.95E+00	3.84E-05	7.30E-01	9.04E-05
16	7.78E 01	4.88E 05	2.92E+00	7.62E 06	1.09E+00	2.60E 05
17	1.09E+00	1.32E-05	4.38E+00	9.76E-07	1.64E+00	5.08E-06
18	1.52E+00	2.80E-06	6.57E+00	8.61E-08	2.46E+00	6.62E-07

* AFE = Annual Frequency of Exceedence ≅ 1/ Return Period

Step 2: Compute the PGA, SA@0.3 and SA@1.0 at each census tract centroid for the eight return periods.

For estimating losses to the building inventory, Hazus uses the ground shaking values calculated at the centroid of the census tract. To incorporate the USGS data into Hazus, the ground shaking values at the centroid were calculated from the grid-based data developed in Step 1.

Two rules were used to calculate the census-tract-based ground shaking values:

1. For census tracts that contain one or more grid points, the average values of the points are assigned to the census tract.

2. For census tracts that do not contain any grid points, the average value of the four nearest grid points is assigned to the census tract.

Using this method, census-tract-based ground motion maps are generated for all eight return periods.

Step 3: Modifying the PGA, SA@0.3 and SA@1.0 at each census tract centroid to represent site-soil conditions for a NEHRP soil class type D.

The USGS data were based on a National Earthquake Hazard Reduction Program (NEHRP) soil class type B/C (medium rock / very dense soil). For this study, NEHRP soil class type D (stiff soil) was assumed for all analyses. To account for the difference in soil class types, the data developed in Step 2 were modified. The procedure described in Chapter 4 of the Hazus technical manual was used for the modification of the ground shaking values.

Average Annualized Earthquake Loss Computation

After the hazard data is processed, an internal analysis module in Hazus is used to transform the losses from all eight scenarios into an Annualized Earthquake Loss (AEL). Figure 17-1 below illustrates schematically a Hazus example of eight loss-numbers plotted against the exceedence probabilities for the ground motions used to calculate these losses.

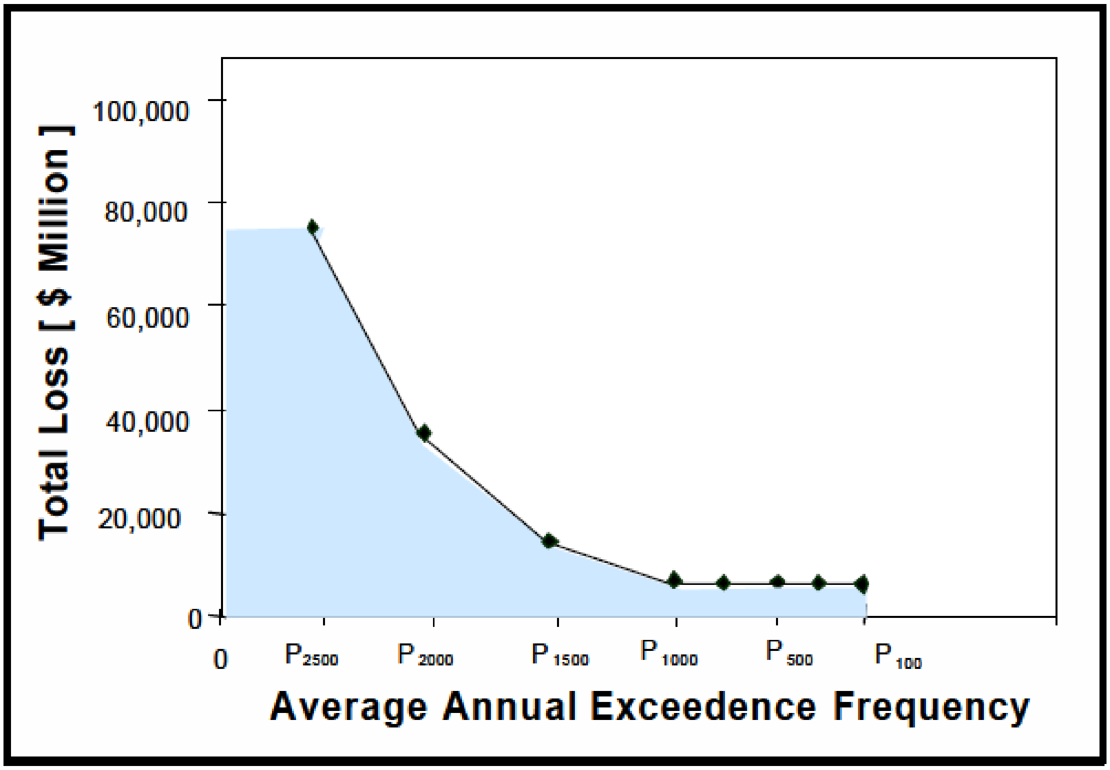

Figure 17-1. Probabilistic Loss Curve

Hazus computes the AEL by estimating the shaded area under thr loss-probability curve shown in Figure 17-1. This area represents an approximation to the AEL and is equivalent to taking the summation of the losses multiplied by their annual probability of occurrence.

The choice for the number of return periods was important for evaluating average annual losses, so that a representative curve could be connected through the points and the area under the probabilistic loss curve be a good approximation. The constraint on the upper bound of the number was computational efficiency vs. improved marginal accuracy. To determine the appropriate number of return periods, a sensitivity study was completed that compared the stability of the AEL results to the number of return periods for 10 metropolitan regions using 5, 8, 12, 15 and 20 return periods. The difference in the AEL results using eight, 12, 15 and 20 return periods was negligible.