FEDERAL EMERGENCY MANAGEMENT AGENCY **FEMA-177 / JUNE 1989**

Estimating Losses From Future Earthquakes

(Panel Report and Technical Background)

EARTHQUAKE HAZARDS REDUCTION SERIES 51

Issued by FEMA in furtherance of the Decade for Natural Disaster Reduction.

FEDERAL EMERGENCY MANAGEMENT AGENCY

Estimating Losses From Future Earthquakes

(Panel Report and Technical Background)

Panel on Earthquake Loss Estimation Methodology
Committee on Earthquake Engineering
Commission on Engineering and Technical Systems
National Research Council

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This study was supported by the Federal Emergency Management Agency under contract No. EMW-86-G-2366 to the National Academy of Sciences. Any opinions, findings, and conclusions or recommendations expressed in this report are those of the committee and do not necessarily reflect the views of the Federal Emergency Management Agency.

Limited number of copies available without charge from:

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Division of Natural Hazard Mitigation
2101 Constitution Avenue, N.W.
Washington, DC 20418
202/334-3312

Printed in the United States of America

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Preface

A key question that must be addressed in earthquake hazard reduction is: How much loss might a city or region experience from future earthquakes? The destructiveness of an earthquake depends on its size, its proximity, and the area's state of preparation. When all three of these elements are adverse they combine to produce a great disaster. Some of these great disasters have permanently impressed themselves upon the public consciousness—Lisbon, 1755; San Francisco, 1906; Messina, 1908; Tokyo, 1923; Alaska, 1964; Mexico City, 1985; and Armenian S.S.R., 1988. Other earthquake disasters with thousands of deaths and extensive property damage did not receive such widespread publicity and are now remembered chiefly by the local inhabitants. Examples of these are San Juan, Argentina, 1944; Agadir, Morocco, 1960; Skopje, Yugoslavia, 1963; and Tangshan, China, 1976.

A significant feature of each of the more modern events is that the disaster focused the attention of the government and the general public on the problem of earthquake hazard and led to the adoption of appropriate seismic engineering requirements in building codes to better prepare these cities for future earthquakes. It would, of course, have been better if these cities had assessed the earthquake hazard and taken loss reduction measures before the event.

According to a 1983 Federal Emergency Management Agency (FEMA) report, in the United States as many as 70 million people in

39 states face significant risk from earthquakes and secondary hazards, such as earthquake-triggered landslides. The recent relatively modest Whittier Narrows, California earthquake, with a magnitude of 5.9 and less than 5 seconds of ground shaking, resulted in property damage exceeding $350 million. Loss of life from a single major earthquake, such as those that have occurred in California in the last 150 years, could exceed 20,000, and economic losses could total more than $60 billion. Moreover, many other cities or regions are vulnerable to earthquake threat: Seattle, Washington; Memphis, Tennessee; Charleston, South Carolina; and Boston, Massachusetts. These places are less prepared to withstand earthquake hazards than is California and they would experience devastating consequences if a major earthquake were to occur.

The enactment in 1977 of the National Earthquake Hazards Reduction Act offered the nation for the first time a substantial and organized effort to address the nation's earthquake hazard mitigation issues. Four principal federal agencies (FEMA, U.S. Geological Survey, National Science Foundation, and National Bureau of Standards), in partnership with state and local governments and also with the private sector, are working on several aspects of earthquake hazards: prediction, risk assessment, land-use planning, better building design and construction of earthquake-resistant buildings, promotion of better building codes, regional economic impact assessment, emergency planning and management, training and education programs, and regional workshops aimed at better technology transfer.

Much information has been developed from the national program in the past 10 years. Now FEMA, working with city, county, and state governments, is preparing guidelines on how to assess the earthquake hazard and how to take appropriate steps to counter it. Major questions facing a city, for example, are: What is the maximum disaster that might be reasonably thought to happen? and What is the maximum probable earthquake disaster that has a significant probability of occurring during the time span of a generation?

Assessing potential earthquake losses is a difficult but essential task to stimulate and guide earthquake mitigation actions. A number of methods have been used for making estimates of future earthquake losses, and there are significant inconsistencies among them. At the request of FEMA, the Committee on Earthquake Engineering undertook the present study. It is intended to be a consensus set of guidelines for a recommended loss estimation methodology.

It is not possible, at present, to predict *accurately* when and where major earthquakes will occur, how many people will die or be injured, and what the damaging effect will be on the wide variety of buildings of different ages and conditions. However, it is possible to make approximate estimates that will indicate the nature and magnitude of the problem faced by a city or region. The Panel on Earthquake Loss Estimation Methodology has prepared this report to serve as a guide for those undertaking to estimate earthquake losses. Although the material in the report represents a consensus, it is likely that some differences in the opinions of experts on loss estimation have not yet been reconciled.

The panel has been aided greatly in its work by many people and organizations. In the acknowledgments that follow some of the contributors to the effort are briefly mentioned. For the Committee on Earthquake Engineering, I express gratitude for this help. For myself, I wish to thank Robert Whitman, panel chairman, all the panel members, the liaison representatives from federal agencies, the staff of the National Research Council, the technical consultants, and others who have inspired and facilitated this task.

George W. Housner, *Chairman*
Committee on Earthquake Engineering

Acknowledgments

The committee wishes to acknowledge the valuable support of Robert Reitherman, who served as technical consultant to this panel study. It also wishes to thank the following individuals for their assistance in providing materials for the study and in critically reviewing and suggesting revisions to the panel report: S. T. Algermissen, Walter W. Hays, and Gerald F. Wieczorek, U.S. Geological Survey; Neville Donovan, Dames & Moore; Bruce Douglas, University of Nevada; Richard Eisner, Bay Area Regional Earthquake Preparedness Project; Peter May, University of Washington, Seattle; Christopher Rojahn, Applied Technology Council; and David Schodek, Harvard University. In particular the committee wishes to thank Arthur Zeizel, project officer, whose agency, the Federal Emergency Management Agency, sponsored the study, for his management coordination and work with the panel; the COSMOS Corporation, which assisted in developing a survey instrument for the user needs workshop; and the National Research Council staff in completing this panel study.

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Aerial view of a portion of the city of Tangshan, China after the earthquake of July 28, 1976 (M 7.8). The causative fault passed under the city, which had little resistance to earthquakes. This combination led to almost total destruction and very large loss of life. ***Photo courtesy of G. Housner.***

Executive Summary

An earthquake loss estimate is a forecast of the effects of a hypothetical earthquake. Depending on its purpose, a loss study may include estimates of deaths and injuries; property losses; loss of function in industries, lifelines, and emergency facilities; homelessness; and economic impacts. This report focuses primarily on loss estimates of the type funded by the Federal Emergency Management Agency (FEMA). They apply to an urban area or region and are intended primarily for use by local and state governments for disaster response and mitigation planning and the formulation of near- and long-term strategies for earthquake hazard reduction. However, the same basic methods, and many of the techniques for carrying out portions of these basic methods, also apply to other types of loss estimates.

Most loss estimates are made for one earthquake or a few earthquakes, specified by magnitude and location. The result is one or more scenarios describing the consequences of the selected earthquake(s). While this is the most common result of a loss study, especially when the objective is disaster response planning, it is not necessarily the most meaningful type of result. When the objective is to select the best allocation of resources for hazard reduction, more information can be derived from a probabilistic risk analysis that considers losses from a spectrum of possible earthquakes, taking into account the relative likelihood of the various magnitudes and locations of the earthquakes.

Even for the type of loss estimate of greatest interest to FEMA, the Panel on Earthquake Loss Estimation Methodology was unable to develop strict standards for conducting loss studies, although such standards might be desirable for the sake of efficiency and consistency. While incorporating some elements of science, loss estimation is still too much of an art for strict standards to be desirable. Instead, the panel has drawn up a general set of guidelines for such studies.

These guidelines first address the planning of a study and the active participation of state and local officials or other intended users. The objectives and scope for a study must be defined carefully, and thought must be given to formation of an inventory of facilities (i.e., buildings and other structures) and networks, so that this inventory can have lasting value, for a variety of purposes, after completion of the study. State and local officials must ultimately disseminate, explain, and make use of a study, and hence must understand the process of preparing the loss estimate. Their early and continuous involvement is essential.

The guidelines also discuss the selection of scenario earthquakes (seismic hazard analysis), the preparation of the inventory, the selection of relationships connecting ground shaking and ground failures to damage and loss, and the evaluation of lifelines, facilities essential for emergency response, and facilities with a potential for causing a very large loss.

Scenario earthquakes should be relatively probable, yet damaging. Use of very large but very infrequent earthquakes for this purpose may cause rejection of loss estimates or a fatalistic attitude. Use of frequent but small events provides little useful information.

Preparation of the inventory should emphasize local sources of data, as much onsite viewing and inspection as the budget allows, and seismically suspicious and critical facilities.

As for motion-damage-loss relationships, valuable information of an empirical nature has been assembled for certain types of buildings in California through the combined efforts of the Insurance Services Office and the large-scale loss estimation projects of the National Oceanic and Atmospheric Administration and the U.S. Geological Survey. An ambitious collection of formalized expert opinion for a broader spectrum of buildings and structures in California has been gathered by the Applied Technology Council, through funding from FEMA. For loss studies in other areas, expert opinion (i.e., a combination of experienced experts, local engineers, architects, building department officials, and lifeline systems operators) or other methods could be used to modify the California-based information for application to the types of facilities found in the areas being studied.

A final recommendation in the guidelines concerns the form of loss estimation reports. It is essential that main findings and conclusions be presented in a way that is useful and understandable to the public and to those who must act on the basis of the report. It is also important to document thoroughly the manner in which the inventory and losses were established. Careful attention must be given to the form and writing of the report to achieve these two objectives.

The guidelines respond to many of the recommendations and desires expressed during an exploratory survey, conducted by the panel, of past and potential users of loss estimates. However, there are two basic areas in which users' desires conflict with the state of the art in loss estimation: (1) the expression of losses as specific numbers, and (2) the identification of individual buildings and other structures likely to be seriously damaged. Loss estimates are approximate, and it is only prudent to report this uncertainty using, for example, a best estimate plus the likely range of losses. Furthermore, a confident prediction of damage to specific facilities requires thorough study, usually beyond the scope of a large-scale loss study, and such predictions may cause legal problems and political controversy.

Even using the best of today's methods and the most experienced expert opinion, losses caused by scenario earthquakes can only be estimated approximately. Overall property loss estimates are often uncertain by a factor of 2 to 3, and estimates of casualties and homeless can be uncertain by a factor of 10. Moreover, the accuracy of estimates will improve only slowly in the future, since a major source for these uncertainties is the very spareness of data on losses during actual earthquakes, as well as the intrinsically difficult inventory problem. Despite these limitations, loss studies—properly conducted and used with an understanding of the methods' strengths and limitations—can be of great value in planning, initiating, and updating programs for earthquake hazard reduction and in emergency planning.

More ambitious than the basic type of loss study is the attempt to evaluate the broader economic impacts of an earthquake, considering such matters as lost revenue and unemployment, on both the directly affected region and a larger area that is linked economically to it. This type of study might also be undertaken to assess the impact of earthquakes on national defense. The panel recognizes the potential value of this type of analysis and recommends the addition of a pilot project to a future loss estimate study.

The panel has also considered the possibility of developing techniques and an operational capability to estimate postearthquake losses within hours after an actual earthquake event, without field reconnaissance, as a basis for better action in disaster response and financial assistance. The panel has little enthusiasm for the prospects of establishing a reliable capability of this kind, because of the large uncertainties in loss predictions and because rapid compilation of actual losses is feasible.

The results of the panel's work are published in two forms: the panel report alone and the panel report with a group of seven working papers. The working papers treat many subjects in detail and are intended for a more technical audience. Chapter 1 of the panel report introduces the issues and discusses the basic underlying method common to most loss estimation studies. The following seven chapters address user needs, ground-shaking hazard, building damage and losses, collateral hazards other than ground shaking, damage and losses to special facilities and urban systems, indirect losses, and rapid postearthquake loss estimates, respectively. Finally, Chapter 9 presents the panel's recommendations on research and development to improve loss estimation capabilities. These are summarized below.

- Compare losses predicted by one or more methods with observed losses, following the next damaging earthquake to strike an urbanized area in the United States.
- Take opportunities to evaluate components of large-scale loss estimation methods (e.g., inventory methods) by comparisons with more accurate small-scale, detailed studies or with available hard data, such as the seismically hazardous building inventories that are now frequently compiled in great detail by local governments in California.
- Perform sensitivity analyses to evaluate the significance, for overall losses, of possible errors at each stage of an analysis.
- With a concerted effort, develop a classification system for buildings and other facilities for use throughout the United States.
- Compare existing inventory methods with the aim of synthesizing their strong points.

- Compare the motion-damage-loss components of various methods with the aim of synthesizing their strong points, and develop a satisfactory quantitative scale for the damaging potential of ground motions.
- Incorporate new developments in the geotechnical field as they become available that will allow more accurate prediction of both the location and severity of ground failures.
- Document precisely how loss studies have been used in hazard reduction and emergency planning efforts.
- Improve the process of collecting loss data of statistical significance immediately after significant earthquakes.

In connection with all of these efforts, special attention should be given to lifelines, emergency response facilities, and storage of hazardous materials.

1

Introduction

An earthquake loss estimate is a description or forecast of the effects of future or hypothetical earthquakes. Loss generally encompasses deaths and casualties; direct repair costs; damage or functional loss to communication, transportation, and other lifeline systems; emergency response and emergency care facilities; the number of homeless people; and the impact on the economic well-being of the region. Earthquake losses may be estimated to:

- Identify especially hazardous geographical areas;
- Identify especially hazardous groups of buildings or other structures;
- Aid in the development of emergency response plans;
- Evaluate overall economic impact;
- Formulate general strategies for earthquake hazard reduction, such as land-use plans or building codes, or evaluate the effectiveness of earthquake programs;
- Support advocacy efforts aimed at establishing priorities and budgets for earthquake programs;
- Aid in obtaining quick estimates, made during the first hours following an actual earthquake, of the approximate impact of the earthquake; and
- Estimate the expected consequences of a predicted earthquake.

The estimation of property losses to assess property insurers' risks has been one of the more common uses of earthquake loss estimates, but is only lightly addressed in this report because the emphasis here is on the broader range of public agency uses.

This report focuses on loss estimates of the type being funded by the Federal Emergency Management Agency (FEMA). They are intended for local and state government use, primarily for disaster response planning and to aid in the formulation of near- and long-term strategies for earthquake hazard reduction. This type of large-scale loss estimate study encompasses a city, region, state, or even the nation, and it looks at more than one type of loss, typically including life loss or casualties, property loss, and functional loss or outages of essential services. A number of such studies have been completed or are under way. Figure 1-1 illustrates the geographic scope of past or in-progress large-scale loss studies, while Table 1-1 lists these major studies.

During the 1970s, the National Oceanic and Atmospheric Administration (NOAA) and the U.S. Geological Survey (USGS) assembled teams of experts, predominantly engineering consultants and federal government geoscientists, who produced large-scale loss studies that set the basic pattern for the scope and methods of others to follow. The first four were devoted to the metropolitan areas of San Francisco (Algermissen et al., 1972), Los Angeles (Algermissen et al., 1973), Puget Sound (Hopper et al., 1975), and Salt Lake City (Rogers et al., 1976). These are sometimes collectively referred to as the NOAA-USGS studies. Some of the more recent studies have been sponsored by FEMA and carried out by consulting firms.

In response to a National Security Council request for an evaluation of potential impacts on the defense industry impacts, FEMA also initiated a recent large-scale effort aimed at modeling the regional economic effects of a major earthquake. This effort involved a study by the Applied Technology Council (ATC) of methods for preparing an inventory of facilities and for estimating damage and functional loss. The result was a report, *Earthquake Damage Evaluation Data for California,* known as ATC-13 (Applied Technology Council, 1985). FEMA also began in-house efforts and supported work by consultants to apply these new methods to selected economic sectors and regions.

Differences exist among the techniques employed in these studies, arising from different levels of earthquake risk in various parts of the country, different objectives and budgets, and different authoring

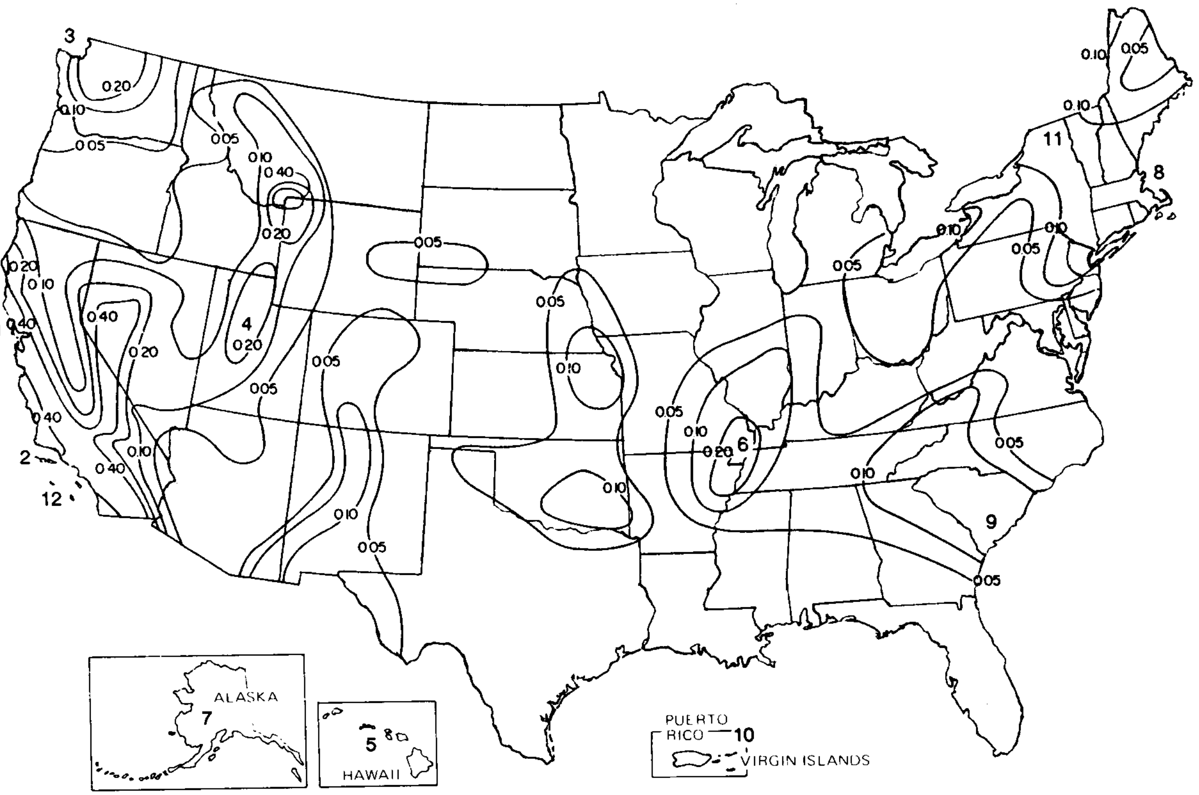

FIGURE 1-1 Areas of the United States where large-scale loss studies have been completed or are in progress (indicated by large numerals, see Table 1-1), shown on a base contour map of effective peak acceleration. Base map source: Building Seismic Safety Council (1985).

TABLE 1-1 Areas of the United States Where Large-Scale Loss Studies Have Been Completed or Are In Progress

Area[a]		Study
1.	San Francisco, California	Algermissen et al., 1972; Davis et al., 1982b; FEMA, 1980; Steinbrugge et al., 1981; Steinbrugge et al., in progress
2.	Los Angeles, California	Algermissen et al., 1973; Blume et al., 1978; FEMA, 1980; Steinbrugge et al., 1981; Davis et al., 1982a; Scawthorn and Gates, 1983; Degenkolb, 1984; California Division of Mines and Geology, in progress
3.	Puget Sound, Washington	Hopper et al., 1975
4.	Salt Lake City, Utah	Rogers et al., 1976; U.S. Geological Survey, in progress
5.	Honolulu, Hawaii	Furomoto et al., 1980; Steinbrugge and Lagorio, 1982
6.	Central United States	Mann et al., 1974; Liu, 1981; Allen and Hoshall et al., 1985
7.	Anchorage, Alaska	Alaska Division of Emergency Services, 1980; URS/Blume, in progress
8.	Boston, Massachusetts	Whitman et al., 1980; URS/Blume, in progress
9.	Charleston, South Carolina	Lindbergh et al., in progress
10.	Puerto Rico and Virgin Islands	Geoscience Associates, 1984 and 1985; Molinelli and Oxman, in progress
11.	Clinton County, New York	Geoscience Associates, in progress
12.	San Diego, California	Reichle et al., in progress

[a] Numbers correspond with studies noted in Figure 1-1.

organizations. Hence, inconsistencies can be found among the results of the various studies, and no clear guidance exists for conducting such studies.

FEMA anticipates the need for future loss estimation efforts. Seeking to encourage studies that are done in a technically sound, efficient, consistent manner that will satisfy the needs of users, FEMA asked the National Research Council to provide "evaluations and recommendations with regard to methodologies which should be used for earthquake loss estimation by FEMA and state and local governments in earthquake preparedness and mitigation planning." This work statement for the council's Panel on Earthquake Loss Estimation Methodology, within the Committee on Earthquake Engineering, required that the applicability of recommended methods be nationwide in scope, or that advice be provided for modifying recommended methods to fit regional variations. In addition to reviewing present methods, FEMA requested recommendations for testing and further development of methods to produce more accurate and comprehensive loss estimates.

The next section of this chapter presents an overview of the basic method used to carry out a loss estimate. This is followed by a discussion in Chapter 2 of the purposes and nature of loss estimates as viewed by potential users, and then by more comprehensive reviews of the techniques and methods available for completing the several parts of a loss estimate. Recommendations for research and development leading to better loss estimates are given in Chapter 9.

Several important points of a general nature must be emphasized:

- The methods examined in this report rely on averaging damage and losses over a large group of facilities, and hence apply to groups of facilities and not to individual buildings. There are techniques for examining in detail the seismic resistance of individual structures, and brief reference will be made to such techniques. However, any such detailed analysis can be expensive and time consuming and therefore generally is not feasible as part of a large-scale study. When methods intended for large numbers of buildings are used to estimate losses for individual buildings, the results may be misleading.
- This report emphasizes large-scale loss estimates, the basic method and some of the detailed techniques of which are applicable to other types of studies.
- No loss estimate prepared today, or in the foreseeable future, can be completely accurate. There are major gaps in our knowledge, both as to the time of occurrence, magnitude, and location of future earthquakes and as to the manner in which the ground and structures will respond to earthquakes. Any loss estimation inherently involves significant uncertainties.
- Despite their limitations, loss studies that are properly conducted and used with an understanding of the methods' limitations can be of great value. These studies have played an important role in developing earthquake programs throughout the country, and are an important tool for initiating effective programs in areas where earthquakes are a significant threat but have received little attention, or where few practical hazard reduction or emergency planning countermeasures exist.

- Loss studies in and of themselves do nothing to reduce seismic risk unless they lead to implementation of hazard reduction or emergency planning measures, or facilitate the development of public policy. Earthquake loss estimation is an important preliminary step toward taking appropriate actions for earthquake loss reduction. This is the most basic purpose underlying earthquake loss estimation. We study earthquake losses so they can be reduced.

BASIC METHOD

As previously noted, earthquake loss estimates may be made for many different purposes. Thus, studies may differ as to the types of losses considered, the extent of the geographical area involved, and the kinds of facilities included. ***Facilities*** is a term of broad scope that includes buildings as well as other ***structures*** such as bridges and utility stations and lifeline systems such as water distribution networks and airports. The detail in which the analysis is carried out and the manner in which the losses are aggregated and presented also may vary. Although the techniques used to carry out various types of studies may differ, a basic underlying method is common to almost all loss estimation studies.

The Two Main Components of an Earthquake Loss Estimation Study

Figure 1-2 illustrates two components comprising the basic structure of a loss estimation study. One component, the seismic hazard analysis, involves the identification and quantitative description of the earthquake (or earthquakes) to be used as a basis for evaluating losses. This part of the study falls primarily within the disciplines of geology and seismology, and this geoscience effort must be coordinated with input from the broad field of civil engineering. The phrase ***seismic hazard*** might seem to refer to all hazards to life and property posed by earthquakes, but the term has a technical meaning restricted to the behavior of the ground, apart from any effects on the built environment.

The second component, the vulnerability analysis, entails analysis of the vulnerability of buildings and other man-made facilities to earthquake damage and the losses that may result from this damage.

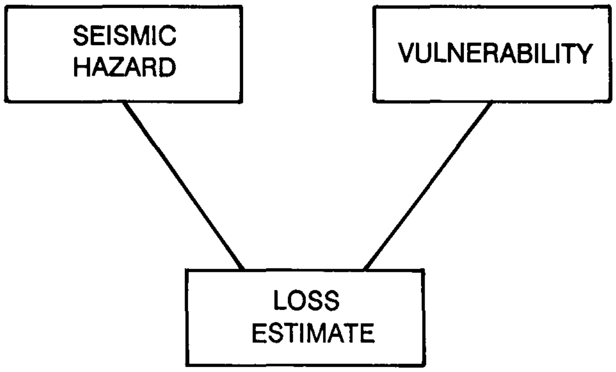

FIGURE 1-2 Basic structure of an earthquake loss estimation study.

This effort primarily involves engineers, architects, and experts in local real estate patterns or socioeconomics, although other disciplines (e.g., utility system operators, urban planners, and disaster preparedness and response specialists) may contribute to identifying steps that can alter the losses caused by damage.

The information assembled from these two components is combined to produce the loss estimate. Close communication among the technical people undertaking the two parts, and with the intended users, is vital to ensure proper coordination.

In most loss estimates, the primary emphasis is on damage and losses caused directly by the shaking of the ground. The bulk of this report deals with the evaluation of the ground-shaking hazard and with the effects of ground shaking on buildings and other facilities. However, other aspects of the seismic hazard, referred to as collateral hazards, often are important. They include fault ruptures, landslides, liquefaction, tsunamis, and seiches.

Landslides may occur in the absence of shaking, but earthquakes often trigger the sliding of susceptible slopes. Liquefaction is the state whereby a normally solid soil (saturated with ground water and usually sands of low density or compaction) turns to a mud-like or fluid consistency when shaken. Tsunamis are seismic sea waves (sometimes popularly called tidal waves). Seiches are sloshing or oscillating waves in bodies of water, generated by earthquakes in reservoirs, lakes, and enclosed harbors. In some earthquakes collateral hazards may be more destructive than the ground-shaking hazard, but the technology for evaluating these hazards and their effects is not as well developed as that relating to the ground-shaking hazard.

In a similar vein, most loss estimates focus on the more or less direct effects of the damage caused by an earthquake: fatalities and injuries, loss of function, and the cost of repairing damage. Various other negative effects are called indirect losses. Other types of indirect but potentially important consequence of damage include fire and flooding from dam failure. Another type of indirect consequence is the economic impact of loss of function on the owners of commercial property, on the region immediately affected by the earthquake, and on a larger region economically linked to the affected area. Again, these losses may be as important as the more direct losses, but the techniques for evaluating them is much more complex and not as well advanced.

The Ground-Shaking Hazard

The basic building block for a description of the ground-shaking hazard is a map displaying the intensities of ground shaking over the study region for an individual earthquake. In general, the intensity will vary over the region, depending on the size and source characteristics of the event, its location, and local geologic materials and topographical conditions. Such a description is a scenario earthquake.

Most loss estimate studies use one or several scenario earthquakes to define the shaking hazard. Loss estimates based on specific earthquakes are relatively easy to understand and explain. In addition, use of specific earthquakes makes it possible to include diverse types of losses, some of which are best described partially by words rather than merely by numbers. The use of several such events allows a range of assumptions and hypotheses to be analyzed and then synthesized in terms of their effects on facilities, without reliance on a single, perhaps unlikely occurrence.

A more comprehensive but difficult to interpret display of the hazard consists of calculating the seismic shaking by considering many possible different earthquakes. Such events can cover a wide range of magnitudes and locations, and each can be assigned a probability of occurrence.

This approach leads finally to probabilities of occurrence for earthquake losses. These results can be presented as loss-frequency curves, which give the annual frequency with which different levels of

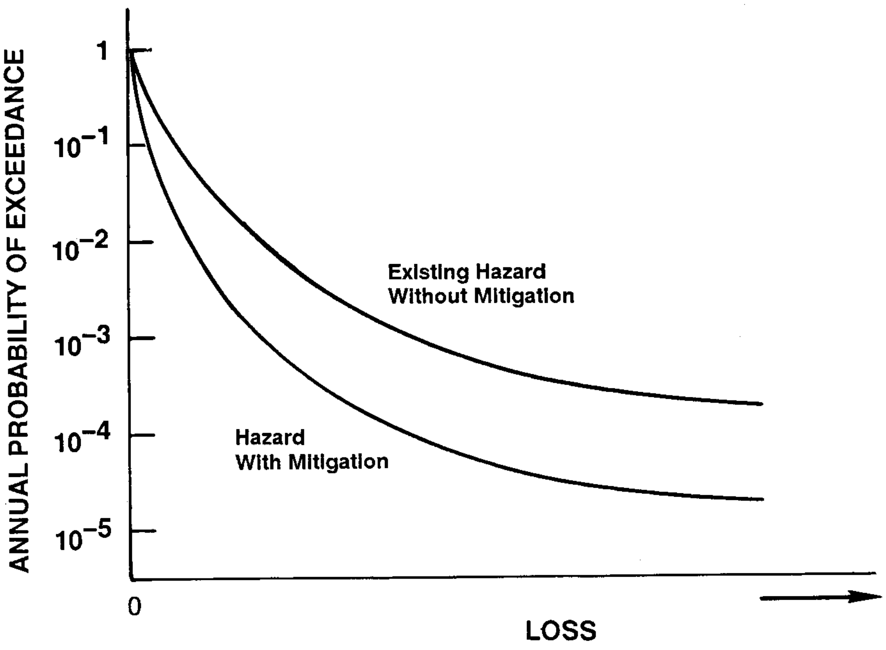

FIGURE 1-3 Loss-frequency curve.

loss are expected to occur (Figure 1-3). Summing these frequencies for levels above a specific value gives, for the study region, the annual probability of exceedance of losses.

Representing the hazard as a loss-frequency curve is ideally suited for study of the relative merits of various mitigative actions. That is, loss-frequency curves corresponding to different possible actions (including no action) may be compared. The method works best when all the consequences of an earthquake can be expressed by a single number, such as dollar loss. When multiple losses of different types are involved, the use of multiple scenario earthquakes finds wider favor.

Regardless of the number of earthquakes used to represent the seismic hazard, there is no single, uncontroversial measure of the damageability of ground motions. For one of the most commonly utilized measures of intensity—Modified Mercalli Intensity (MMI)—there are even basic disagreements as to the interpretation and definition of the scale.

A strong need exists for communication at the beginning of a loss study among those who will evaluate the ground-shaking hazard and ground failures, those who will determine the losses resulting from that seismic hazard, and those who will utilize the results of the study.

Vulnerability

There are two steps in a vulnerability analysis: (1) developing an inventory of the buildings and other facilities to be considered in the study, and (2) establishing for each inventory category the relationships among intensity of ground shaking (and, in some cases, ground failures), resulting damage, and associated losses.

A key step is to develop a list of the categories of facilities to be considered, that is, to select a classification system. Selection of this system requires a compromise between different objectives. On the one hand, a very detailed classification system, with many categories, allows fine distinction to be made among buildings with different seismic resistance. On the other hand, a coarse classification system with only a few categories simplifies the inventory effort and makes it more economical. It is also inappropriate for a classification scheme to divide facilities into many different categories if the underlying state of the art is unable to distinguish among the predicted performance of the categories. Reaching an optimum compromise requires close communication among the parties conducting the loss study.

For purposes of evaluating damage, facilities are usually inventoried by placing them in different groups.

- Buildings that provide working space or residences for people;
- Lifelines, such as transportation, communications, water, sewage, and electricity systems, that are vital to the functioning of an area;
- Essential facilities, such as hospitals, and fire and police stations, that are vital to postdisaster response; and
- Facilities with a potential for large loss, such as large and densely occupied buildings, dams, and chemical plants.

Lifelines must be treated differently than buildings because they form interconnected systems that extend over large areas. Essential facilities, if they are to be included, must receive more careful attention and individual surveys and analyses. Facilities with a potential for large loss pose a very special problem. Clearly their presence and potential for large loss must be noted, but losses cannot actually be estimated without analyses of the likelihood that potential damage will actually occur in a given scenario earthquake, and this requires very detailed study well beyond the scope of a typical loss estimate. It is easier, for example, to map the area that would be flooded if a certain dam were to fail than it is to determine whether the dam actually would fail in various earthquakes.

CONSIDERATIONS OF UNCERTAINTY

The foregoing discussion has presumed that loss estimates take the form of scenarios or a loss-frequency curve. For the former, one or more particular earthquakes are postulated to occur, and the losses expected from each are described. For the latter representation, the probabilities of various levels of loss are indicated. Whichever method is used, the uncertainty in the loss estimates should be indicated, such as by giving a range of possible losses.

The uncertainties in loss estimates derive from several sources. First is uncertainty in the ground-motion intensity and ground failures for a given event. Second is uncertainty in estimating damage given the intensity and ground failures. Third is uncertainty in estimating the losses given damage to the facility. Finally there is uncertainty in the process of inventorying the number of facilities in each building classification and geographic area. Each of these elements could be made more precise with additional effort and resources, but uncertainties are inevitable in any practical study of earthquake losses and should be expressed and quantified.

2

User Needs

In requesting this study, FEMA emphasized the need to learn users' opinions concerning the applicability of loss estimate studies as well as how studies should be conducted and presented in the future. Users were defined primarily as state and local officials responsible for earthquake hazard reduction and disaster response planning.

A user needs workshop was held in September 1986. There was a broad spectrum of invitees from all levels and aspects of government. In addition to discussions in large and small groups, questionnaires were used both before and at the end of the workshop to evaluate the thinking of the participants.

Owing to the breadth of the potential user community and limitations on funds and time, this effort was not a scientifically designed survey or experiment. Nonetheless the undertaking yielded considerable insight into the needs and thoughts of those who ultimately must use the results of loss estimates.

The user group did not consider previous studies to have been as useful as they wished. The discussions also emphasized two questions: Who will use a loss study? and For what purpose? These two questions must be answered prior to selecting methods for producing loss estimates.

CONFLICTS

The study of user needs clearly brought out several important conflicts between what is desired and what is feasible, among different groups within the user community, and between the users and producers of loss estimates.

The Scale of Studies

Loss estimates of primary interest to this study typically are made on a regional basis, that is, they involve an area encompassing a number of political jurisdictions. Actions to reduce hazards must, however, usually be undertaken by the individual jurisdictions. Officials working on this local level consider it vital that loss estimates be disaggregated to the local level—a need that can be in conflict with procedures often used to assemble inventories and compute losses.

Specificity Versus Liability

Local officials also would like to know precisely which buildings or other facilities are most susceptible to damage, so that mitigative actions can be targeted. On the other hand, those making loss estimates fear legal or political reprisals if they are specific in identifying potentially dangerous structures, and consider it essential that they preserve anonymity by lumping together considerable numbers of structures and evaluating losses only for such groups.

The Scenario Earthquake

The user group indicated that loss studies should focus on a relatively probable and yet damaging earthquake, and it was deemed important that losses be estimated separately for different times of the day. Using too large and too improbable an earthquake may decrease the usefulness of a study. However, the group did not indicate a suitable level of probability for a scenario earthquake. There was little enthusiasm for being presented with losses from several different scenario earthquakes having different probabilities.

Accuracy and Uncertainty

Several users indicated that the usefulness and credibility of a study decrease when it gives a wide range of answers to determining potential loss from a scenario earthquake, even though they realized the considerable inevitable uncertainty in loss estimates.

Cost Sharing

Another theme that arose in the discussions involved a basic financial conflict among different levels of government. A recent trend has been the shifting of costs of earthquake programs from the federal government to lower levels, or in other words increasing state and local cost sharing. However, the user group said that funds available for such studies at state and local levels are generally inadequate.

SPECIFIC SUGGESTIONS

Perhaps the most important point to emerge from the discussion of user needs is the need for increased involvement of state and local officials and policymakers in the entire loss study process. This involvement has an educational value apart from the value of the report that is eventually produced. The state and local officials must ultimately use, disseminate, and explain the results of a study and hence must understand just what has been done in preparing the loss estimate. When loss studies are to be used by advocates of seismic policy and planning, officials must be involved in the loss estimation study process, and reports must be understandable and timely. The technical experts involved in producing the study will also benefit from an increased awareness of users' needs and attitudes.

The survey of user needs identified types of facilities about which it is most essential to have reliable loss estimates. High on the list are dams, emergency public facilities (such as hospitals), and electric, water distribution, and highway systems. Also expressed was a need to know the location and vulnerability of facilities containing hazardous materials.

Finally, the user group urged that inventories be prepared in such a way that the information is available to update loss estimates and can be disaggregated for nonearthquake purposes.

3

Ground-Shaking Hazard

This chapter examines the selection of scenario earthquakes. Use of scenario earthquakes is not the only way to address loss estimation, but it is the most common method. There are two general approaches to evaluating scenario earthquakes that are commonly referred to as deterministic and probabilistic methods, although elements of judgment and uncertainty are present in both.

DETERMINISTIC METHODS

In this method, one or more earthquakes are postulated without explicit consideration of the probability that those events will occur. The most common form of this method is use of the largest earthquake known to have occurred in a region, and this event is termed the historical maximum earthquake. This approach is based on a premise that is geologically sound as well as intuitively convincing: if an earthquake has occurred once, it can occur again. Usually this approach is acceptable to both the governmental users of loss estimates and the general public.

Once a decision to adopt this basic approach has been made, various questions must be answered in order to establish a scenario earthquake. For example, will it be assumed that the same earthquake reoccurs with the same extent, location, and type of faulting? The distribution of ground-shaking intensities outward from the earthquake may have been recorded, and can then be used directly. If this distribution was not thoroughly recorded, it will be necessary to use attenuation relationships (derived from analysis of data from many different earthquakes) to calculate some or all of this distribution. Alternatively, it may be decided that a different location should be considered, perhaps closer to the region being studied. In this case, use of attenuation relationships to calculate intensities is essential.

If there are multiple faults near the region being studied, it will generally be desirable to consider separately the historical maximum earthquake for each fault. This is because each of these several earthquakes may produce the largest losses in some portion of the region.

In some studies, two levels of earthquakes have been used: the historical maximum earthquake and a smaller earthquake chosen by judgment. The smaller earthquake has often been taken to have a magnitude one unit less than the historical maximum earthquake. This practice has been adopted when planning for a response to several levels of disaster is deemed desirable, or when a repetition in the near future of a large historical maximum earthquake lacks credibility.

There are also instances where earth scientists present convincing evidence that an earthquake larger or closer than the historical maximum event should be considered. This may happen when there is geological evidence of earthquakes more severe than those that have occurred in historic time.

The proper characteristics of the scenario earthquake for use in planning how to respond to a validated earthquake prediction would be the predicted earthquake's magnitude, location, or other available seismological information accompanying the prediction. Except for the greater potential for controversy concerning predicted earthquakes, the other aspects of loss estimation are the same for nonpredicted scenario earthquakes.

It is clear that this deterministic approach involves some judgment and uncertainty. Even in the most seismic regions of the country, no one knows when the next major earthquake will occur or just what it will be like; almost certainly there will be surprises. There is no clear definition of the largest possible earthquake—some expert can always envision a larger event—and even if there were a well-defined maximum earthquake, it is not obvious that this immense earthquake is the proper basis for hazard reduction planning. As one moves away from use of the actual historical maximum earthquake, and as use of attenuation relationships comes into play, uncertainty increases. As stated earlier, it is desirable that at least a rough indication of the probability of occurrence be attached to all scenario earthquakes, if only to convey to users and the public some indication of the likelihood of such an event.

PROBABILISTIC METHODS

As just noted, there are two situations where attempts to use the historical maximum earthquake run into difficulties. At one extreme is the situation where a very large earthquake has occurred within recorded history, but it is thought unlikely that it will reoccur soon and in the same locale. The other extreme is the situation where it is thought relatively likely that there can be an earthquake larger than the historical maximum earthquake. ("Historical" merely refers to a brief sample of the geologic timespan, up to about 400 years in the eastern United States and 200 years in the West, and some earthquakes that occur only once every several centuries are unlikely to be included.) For such situations, it would be useful to have a systematic method for selecting the scenario earthquakes that meet the criteria of being plausible but damaging.

Probabilistic hazard analysis offers this possibility, and is discussed in a report of the National Research Council (1987). The elements of this method are sketched in Figure 3-1. Information is required concerning: the location of potential sources (such as known faults) of earthquakes, the probability that different magnitudes will occur within or along each source, and the attenuation of intensity away from the source, including uncertainty in the attenuation relation. This information is then formally combined to produce a ground-shaking versus hazard curve (Figure 3-1D), giving the probability that any ground-motion level will be exceeded. An exceedance probability is selected and the associated ground-motion level (target level) is found from the hazard curve.

Finally, the scenario earthquake is defined as the most likely event among those that produce ground motions more intense than the target level. The technology for this type of analysis is well advanced, although there are often problems of statistically inadequate data for evaluating parameters required by the theory.

One difficulty in the use of probabilistic ground-shaking hazard analysis is in selection of the probability of exceedance to be used

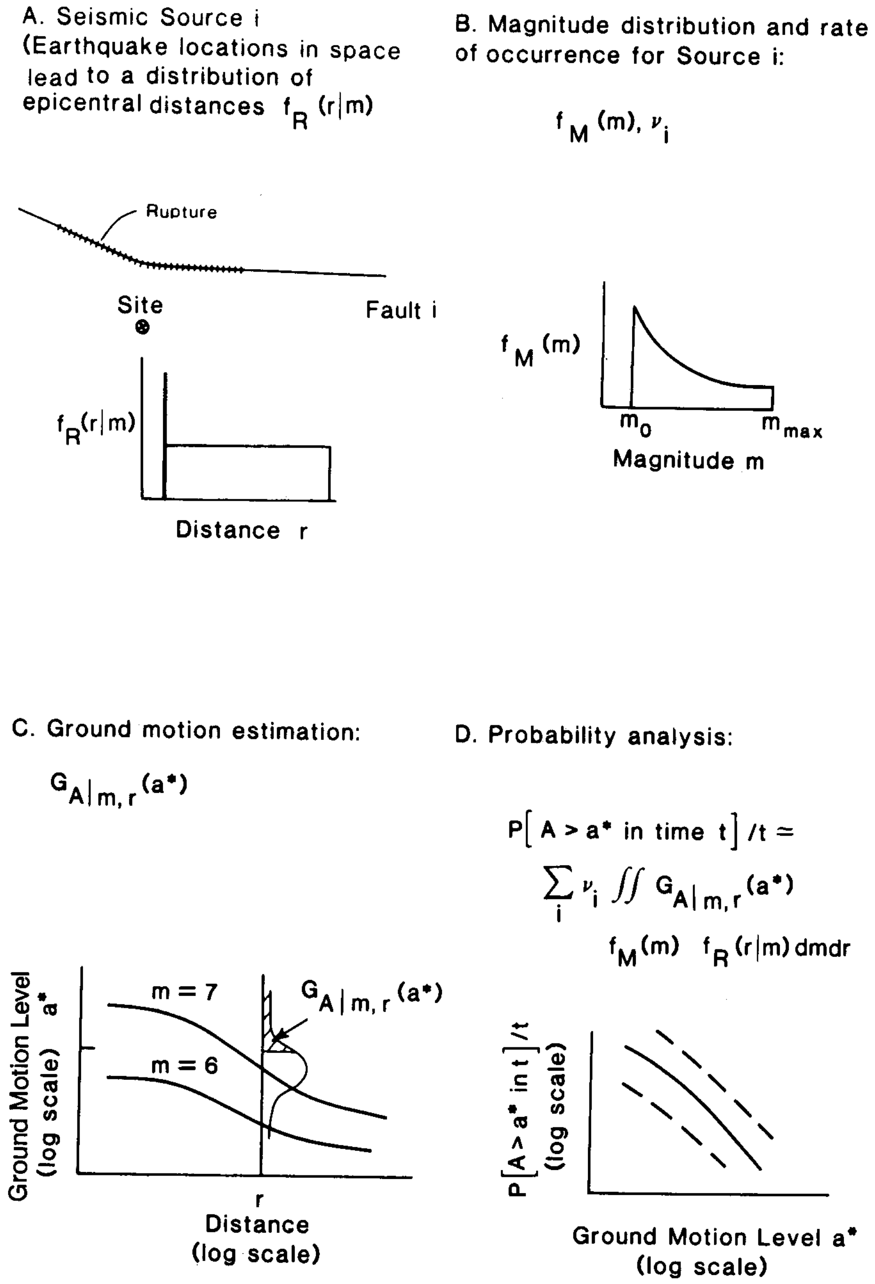

FIGURE 3-1 Graphs indicating probabilistic seismic hazard analysis steps.

for defining a scenario earthquake. There are no generally accepted rules for this purpose. Some of the historical maximum earthquakes used for earlier loss studies have annual probabilities of about .002, which is equivalent to a mean recurrence interval of 500 years.

The panel rejects the notion of a single standard probability at this time, but accepts that, in the absence of a suitable historical maximum earthquake, a scenario earthquake with an annual probability in the range from .001 to .005 is reasonable for disaster response and mitigation planning. Despite the lack of definite criteria, use of probabilistic seismic hazard analysis offers the only rational means for selecting scenario earthquakes for many parts of the country.

DESCRIBING INTENSITY OF GROUND MOTION

As noted earlier, there is no generally accepted, objective, quantitative scale for measuring the damaging effects of strong ground motion. This is because different buildings, structures, or other facilities respond in different degrees to various aspects (e.g., predominant frequency, duration, and so on) of ground motion.

Most U.S. loss estimates have used MMI as a scale for the intensity of ground shaking. This scale involves subjective evaluation of the effects of ground shaking, and its use is subject to abuse and misinterpretation. However, in most parts of the country the historical seismic record is known only in terms of MMI. Instrumentally recorded strong-motion data are much more sparse.

While urging continued research to develop a satisfactory quantitative measure of ground-motion severity, the panel accepts the continued use of MMI as a basis for the usual loss estimate study.

One aspect of MMI that does require careful attention is the meaning and use of intensities XI and XII. The scale's criteria for these levels emphasize observations of ground failure, some of which may occur when other indicators of shaking severity imply a MMI as low as VI. The use of high MMI values in a loss estimate requires explicit explanation to avoid misunderstanding. Some on the panel interpret the MMI scale as implying that intensity X represents maximum possible ground shaking. Others feel that ground shaking stronger than that associated with MMI X is possible, and there have been some instances in which loss estimators have used MMI XI and XII to represent increasingly strong ground shaking apart from ground failures.

The panel recommends that MMI XI and XII *not* be used to indicate increased intensities of ground shaking. If this is nonetheless done, it is essential that the interpretation of these intensity levels be set forth very clearly, and an explicit statement of how the MMI scale was interpreted should be included in any study where it is used.

EFFECTS OF LOCAL SITE CONDITIONS

Local site conditions can have a great effect on earthquake losses. Greater losses often occur because of ground failures, increased intensity of shaking for some soil and topographic conditions, and selective amplification of ground motion at the frequencies critical to structural response. It is important to take site effects into account in a loss estimate. While geotechnical data collected at individual construction sites can be very valuable in this effort, more generalized geologic mapping of districts and zones in a city or region is also useful and can lead to refinements in seismic hazard analyses.

The essential requirement is to make clear whether the intensity in a scenario earthquake applies to the ground as it is locally found (i.e., no further correction for local soil conditions required) or whether it applies to some standard ground condition and must be further modified for actual local conditions. This is a matter requiring good communication among seismologists, geologists, and engineers.

4

Building Damage and Losses

CLASSIFICATION OF BUILDINGS

For loss estimation purposes, the buildings within a region are put into a number of categories according to a construction classification system. This is the starting point in the vulnerability analysis process, as shown in Figure 4-1.

The primary consideration in developing a classification scheme is differences in the resistance of various buildings to damage during ground shaking. Some of the factors taken into account are the type of structural system, the materials of construction, the size of the building, and the degree to which structural features limiting damage have been provided during design and construction. The age of a building is sometimes used as an indirect indicator of seismic design level in areas where seismic codes have been adopted, and it can indicate typical construction practice in a given region.

In the planning stages for a study, the steps of selecting a classification system, developing methods to prepare the inventory, and assembling motion-damage information are all interdependent. That is, the choice of a classification system depends on the availability of information for the inventory and the effort that can be put into carrying out the inventory. The availability of data relating motion and damage for various kinds of construction is also limited, and this similarly restricts the classification options.

This 14-story reinforced-concrete apartment building experienced extensive damage to the spandrel beams during the 1964 Great Alaska earthquake (M 8.3–8.6). Its twin in another location in Anchorage was similarly damaged. Structures that have adequate strength to resist moderate shaking may not be able to withstand strong ground shaking. *Photo courtesy of G. Housner.*

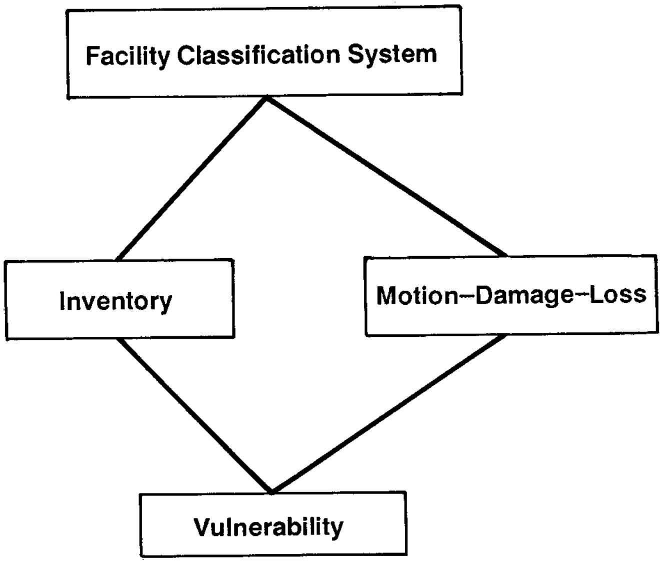

FIGURE 4-1 Structure of the vulnerability analysis portion of an earthquake loss estimate study for buildings, lifelines, facilities with essential emergency roles, and facilities with potentional for large loss.

The most commonly used classification system in the United States for estimation of earthquake loss is that developed by Algermissen and Steinbrugge (1984). As shown in Table 4-1, this scheme has 21 categories, determined primarily by the type of information readily available to property insurance companies. A more recent classification system used in the ATC-13 study (Applied Technology Council, 1985) has over 40 categories, with height emphasized as a factor. Both of these systems have been heavily dependent on the work of experts in California. For loss studies elsewhere in the United States, these basic schemes should be reviewed and possibly modified and simplified to take into account local construction variations and problems of assembling an adequate inventory. For example, in the study of six cities in the midwestern United States (Allen and Hoshall et al., 1985), only eight building construction categories were used.

INVENTORY

Preparation of the inventory is usually the most time-consuming and costly aspect of a loss study. It is also often the most frustrating,

TABLE 4-1 Construction Classes Used in the ISO and NOAA/USGS Methods

Building Class	Brief Description of Building Subclasses
1A-1	Wood-frame and stuccoed frame dwellings regardless of area and height
1A-2	Wood-frame and stuccoed frame buildings, other than dwellings not exceeding three stories in height or 3,000 square feet in ground floor area
1A-3	Wood-frame and stuccoed frame structures not exceeding three stories in height regardless of area
1B	Wood-frame and stuccoed frame buildings not qualifying under class 1A
2A	One-story, all metal; floor area less than 20,000 square feet
2B	All metal buildings not under 2A
3A	Steel frame, superior damage control features
3B	Steel frame, ordinary damage control features
3C	Steel frame, intermediate damage control features (between 3A and 3B)
3D	Steel frame, floors and roofs not concrete
4A	Reinforced concrete, superior damage control features
4B	Reinforced concrete, ordinary damage control features
4C	Reinforced concrete, intermediate damage control features (between 4A and 4B)
4D	Reinforced concrete, precast reinforced concrete, lift slab
4E	Reinforced concrete, floors and roofs not concrete
5A	Mixed construction, small buildings and dwellings
5B	Mixed construction, superior damage control features
5C	Mixed construction, ordinary damage control features
5D	Mixed construction, intermediate damage control features
5E	Mixed construction, unreinforced masonry
6	Buildings specifically designed to be earthquake resistant

SOURCE: Algermissen and Steinbrugge (1984).

since in principle it is possible to develop a perfect inventory, but in practice compromises must always be made. Time and budget constraints lead to shortcuts and extrapolations, but evaluation of building seismic performance necessarily involves the use of reliable building data not obtainable by shortcut methods.

Facility inventories can be maintained and later used both for updating initial loss estimates and in determining follow-up loss estimates for facilities or geographic areas or for other purposes within a study region. Therefore, the panel is persuaded that it is wiser in the long run to compile systematically an inventory that is as accurate as possible under the circumstances and resources available.

There are three interrelated factors to consider at the outset of a project: the content of the inventory, the process of assembling the information, and the manner in which the data are to be recorded or stored.

Content of the Inventory

What information concerning buildings is required? The basic minimum data are:

- Geographic location;
- Category of seismic resistance;
- Economic value of the building;
- Number of occupants, at different times of day; and
- Type of occupancy of the building (e.g., housing, commercial, or essential facility).

Seisimic resistance must be derived from information on such characteristics as construction class, age, height, and so on. The meaning of economic value may differ according to the purpose of the loss study, as discussed below. Other information, such as the function of the building (e.g., office or light manufacturing), may also be desired.

A key problem is the degree of disaggregation or aggregation of this information. At one extreme, the inventory may list only the total economic value and total number of occupants aggregated for all buildings in a given construction class within some geographical area. At the other extreme each building might be listed separately and then aggregated for purposes of predicting losses. Obviously this question is strongly related to how the inventory is to be compiled and how the information is to be recorded.

Another key question is the smallest geographical area to be used. As discussed in the section on user needs, it should be possible to disaggregate losses to any local political unit, which in the case of a large city may mean wards, precincts, or districts. Census tracts or postal zip codes also are convenient minimum geographical units, but if used they may require localized modifications to make the tract or zip code data correspond to other boundary lines.

There are a number of possible definitions for economic value, and the choice depends primarily on the purpose of the loss estimation study. Cash value and replacement cost have both been used. For most studies, it seems appropriate to use replacement cost.

Carrying Out the Inventory

The inventory process is a matter of assembling and using available sources of information, carrying out some amount of onsite inspection, and applying some judgment. Census data are valuable, particularly for housing, and generally some local records are available from, for example, planning departments and assessors' offices. The most difficult information to pin down is the seismic resistance or construction class. Here is where the experience of local engineers, building officials, and architects, combined with judgment, have to play a major role. Field sampling is also useful to define typical local construction patterns.

It might seem ideal to develop a listing of all individual buildings, but this seldom is feasible. While some data files, such as those maintained by assessors, are typically compiled for individual properties, they are unlikely to contain adequate information for assigning seismic resistance. Moreover, for loss estimation purposes it is quite satisfactory to have crude data for the more seismically resistant buildings. Attention should be concentrated on developing a reasonably good inventory of the seismically suspicious buildings of high vulnerability that will incur the bulk of the serious damage (Arnold and Eisner, 1984). Onsite surveys to identify and enumerate these buildings are vital to a satisfactory loss estimate. One example of a seismically suspicious construction class is unreinforced masonry, which is often concentrated in recognizable districts.

ATC-13 describes three methods for assembling an inventory, ranging from situations where detailed information is available in local files to cases where very few data are available. For the common latter situations, a method for abstracting an inventory from socioeconomic data is described. The panel feels that extensive field studies would be necessary to validate this approach, and that the varieties of situations to be encountered make success unlikely. The panel believes that corresponding sums of money spent on direct observation of buildings to discern specific seismic performance indicators would yield more useful results. There appears to be only a weak correlation between socioeconomic characteristics, such as number of employees and the Standard Industrial Classification number indicating economic sector, and construction characteristics relevant to earthquake loss estimation. While a convenient data file, such socioeconomic information is not particularly relevant to the task of producing an inventory of facilities according to construction classes.

Recording the Inventory

There are several reasons for collecting the inventory data in a format consistent with computerization. At a minimum the data should be stored in such a way that losses from several different earthquakes can be evaluated. It is desirable that data be retained so that updated loss estimates can be made in the future. Finally, information in an inventory is potentially valuable for entirely different purposes, such as economic development planning and city planning.

It is vital to include meetings with various potential users of inventory information at the beginning of a loss estimate study. Such discussions will indicate how much effort is justified in obtaining and formatting the inventory so that it can be accessed and used by various governmental agencies. A key question is whether there is the will and the means to maintain the inventory in an updated condition. Where a significant long-term effort appears warranted, use can be made of some impressive digital mapping technology well along in its development by USGS and others (Alexander, 1987; Brabb, 1985; Schulz et al., 1983).

Role for a National Data Base

Creation and maintenance of a complete nationwide data base on the construction characteristics of all buildings is an impractical idea. However, some incremental, less geographically complete projects, or efforts limited to simplified construction classifications, may be feasible and desirable and should be investigated. Modest improvements in the compilation of data might include:

- Comparing classification schemes so that future loss studies collect and organize their data in a format similar to either the ATC-13 or NOAA-USGS construction classes, or to some new scheme.
- Suggesting data that could be reliably collected at virtually no additional cost by the U.S. Bureau of the Census. Noting the height of a building (e.g., placing it in one of three or four ranges of height in terms of numbers of stories) may be such a possibility.
- Investigating the potential of using the FEMA Multihazard Vulnerability Survey method (FEMA, 1985) in connection with large-scale earthquake loss estimation rather than for the field survey of individual essential emergency operation facilities and life support systems, which was the initial purpose for devising this multihazard survey method. Field sampling of buildings previously surveyed by

this method and easy access by earthquake loss estimators to Multihazard Survey data computerized by FEMA, are promising ideas. The applicability of the data collection and analysis components of the FEMA Multihazard Vulnerability Survey method (which includes wind and flood hazards in its scope as well as earthquakes, depending on the site's location) should be evaluated in the context of loss estimation.

MOTION-DAMAGE RELATIONSHIPS

Identifying the relationship between the intensity of ground shaking and the damage experienced by a group of generally similar structures, or a construction class, is essential to vulnerability analyses. One intensity/damage relationship is needed for each type of facility in the classification system.

There are several ways in which this relationship may be expressed and evaluated.

Use of Mean Values

The most common method for presenting the relationship between ground shaking and damage is by a loss ratio curve. Typical curves, developed some years ago by Steinbrugge et al. (1984) for the Insurance Services Office (ISO), are shown in Figure 4-2. The curves truncate at MMI IX because of the interpretation by ISO of the MMI scale: intensities above IX were taken to represent ground failures rather than ground shaking. (The classes of construction are those in Table 4-1.) Percent loss, also called mean damage ratio or mean damage factor, is the cost of damage expressed as a percentage of replacement value. This is a mean value for a large population of buildings of a given class.

Relationships of this form are particularly useful when only the expected value of the dollar cost of damage is evaluated in a loss study.

Information About Distribution of Damage

For some purposes, knowing only the mean level of damage is inadequate. For example, serious casualties and injuries are usually related to extreme damage experienced by a minority of buildings.

Split-level houses that were deficient in earthquake resistance collapsed during the 1971 San Fernando, California earthquake (M 6.6). Well-built houses in the area survived, experiencing only cracks in plaster.

Compton Boulevard between Alameda and Tamarind streets following the March 10, 1933, Long Beach earthquake (M 6.2). So many walls collapsed that the street was completely blocked by bricks. The poor performance of these buildings led to changes in the building code that prohibited the construction of unreinforced-brick buildings.

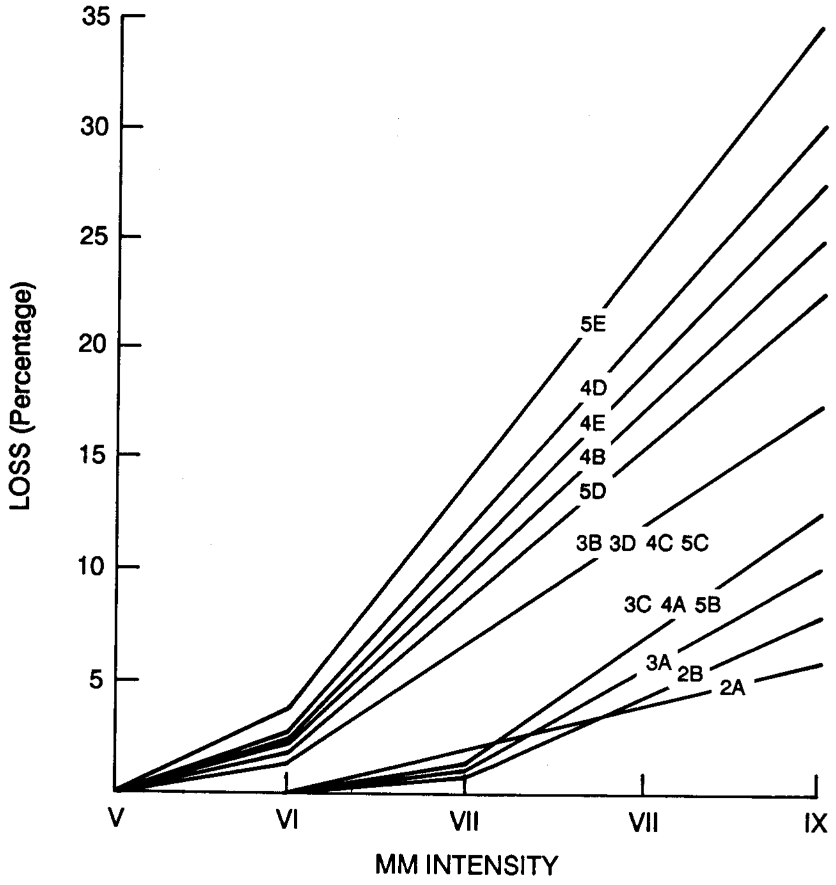

FIGURE 4-2 Loss ratio versus Modified Mercalli Intensity (mean damage ratio curves). Designations on curves refer to Table 4-1 construction classes. Source: Algermissen and Steinbrugge (1984).

One method for expressing the distribution of damage is a damage probability matrix (DPM) (Table 4-2).[1] The spectrum of damage,

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[1] In Table 4-2, the original source (ATC-13) used MMI levels XI and XII to represent increasingly severe shaking severities beyond MMI X. As noted earlier, confusion results when this is not explicitly stated, because a literal reading of XI and XII indicates ground failure and at XII "total" damage. In Table 4-2 the DPM has been truncated at MMI X to avoid different portrayals of MMI when definitions for MMI XI and XII may not be clear to the reader.

TABLE 4-2 A Damage Probability Matrix Form

Damage State	Damage Factor Range (percent)	Central Damage Factor (percent)	Probability of Damage (in percent) by MMI and Damage State[a]				
			VI	VII	VIII	IX	X
1--None	0	0.0	95.0	49.0	30	14	3
2--Slight	0-1	0.5	3.0	38.0	40	30	10
3--Light	1-10	5.0	1.5	8.0	16	24	30
4--Moderate	10-30	20.0	0.4	2.0	8	16	26
5--Heavy	30-60	45.0	0.1	1.5	3	10	18
6--Major	60-100	80.0	--	1.0	2	4	10
7--Destroyed	100	100.0	--	0.5	1	2	3

NOTE: These definitions are used as a guideline:

1--None: no damage.
2--Slight: limited localized minor damage not requiring repair.
3--Light: significant localized damage of some components generally not requiring repair.
4--Moderate: significant localized damage of many components warranting repair.
5--Heavy: extensive damage requiring major repairs.
6--Major: major widespread damage that may result in the facility being razed.
7--Destroyed: total destruction of the majority of the facility.

[a] Example values are listed.

SOURCE: Applied Technology Council (1985).

from none to total, is divided into damage states, each of which is described both by words and by a range of damage ratios. For each intensity of ground shaking, numbers in a column give the fractions of buildings experiencing different damage states; the numbers in each column sum to unity.

Fragility curves (Figure 4-3) provide essentially the same information as does a DPM, but in graphical rather than tabular form. Each curve gives, as a function of the intensity of ground shaking, the probability that the indicated damage state is equalled or exceeded. While the curves shown in Figure 4-3 are only for one construction class (wood frame), the general form is typical. The steeper the slope of a curve, the less the variability in expected performance for that damage state. The steep slope of low-damage curves 1 and 2 implies that it is relatively easy to predict that this class will have only slight structural damage or only nonstructural damage at low intensities.

DPMs and fragility curves provide the same information in different formats. Thus, the choice between DPMs and fragility curves is a matter of style and precedent. The DPM originated in connection with loss estimates for buildings. Use of fragility curves developed in studies of the performance of mechanical equipment and have been applied in seismic risk studies for facilities such as nuclear power plants. It is important to note that mean loss ratios may be calculated from the information in DPMs or fragility curves, but the reverse is not true; information about the distribution of damage about a mean cannot be inferred from a mean loss ratio curve.

Evaluating Motion-Damage Relationships

The loss ratio curves in Figure 4-2 were constructed, employing considerable judgment, using loss data gathered during various earthquakes, principally those occurring in California and a few other western states, along with data from foreign earthquakes where construction has been compatible. Actual data of this type are most complete for wood-frame dwellings (these data do not appear in Figure 4-2), and more judgment has been required to construct curves applicable to other buildings.

In a few cases, DPMs have been constructed using data from actual earthquakes, tempered with judgment. A recent report compiled data on earthquake damage from a variety of sources (Thiel and Zsutty, 1987) and indicates the usefulness of hard data about past performance in studies that attempt to estimate future performance. However, for many types of buildings, and especially for those in areas that have experienced few if any damaging earthquakes, actual data are either very sparse or nonexistent. For such buildings, it is necessary to rely on expert opinion to develop loss ratio curves, DPMs, or fragility curves.

A systematized Delphi method approach was used to synthesize diverse expert opinions into the family of DPMs found in the ATC-13 study. The panel examined the method used to develop these DPMs and considered the credibility of the results. Concern was expressed that the ATC-13 DPMs underestimated the dispersion in the damage because zero probabilities were assigned in each column to damage states away from the predominant damage state. However, in the ATC-13 method, each matrix is meant to apply for average California

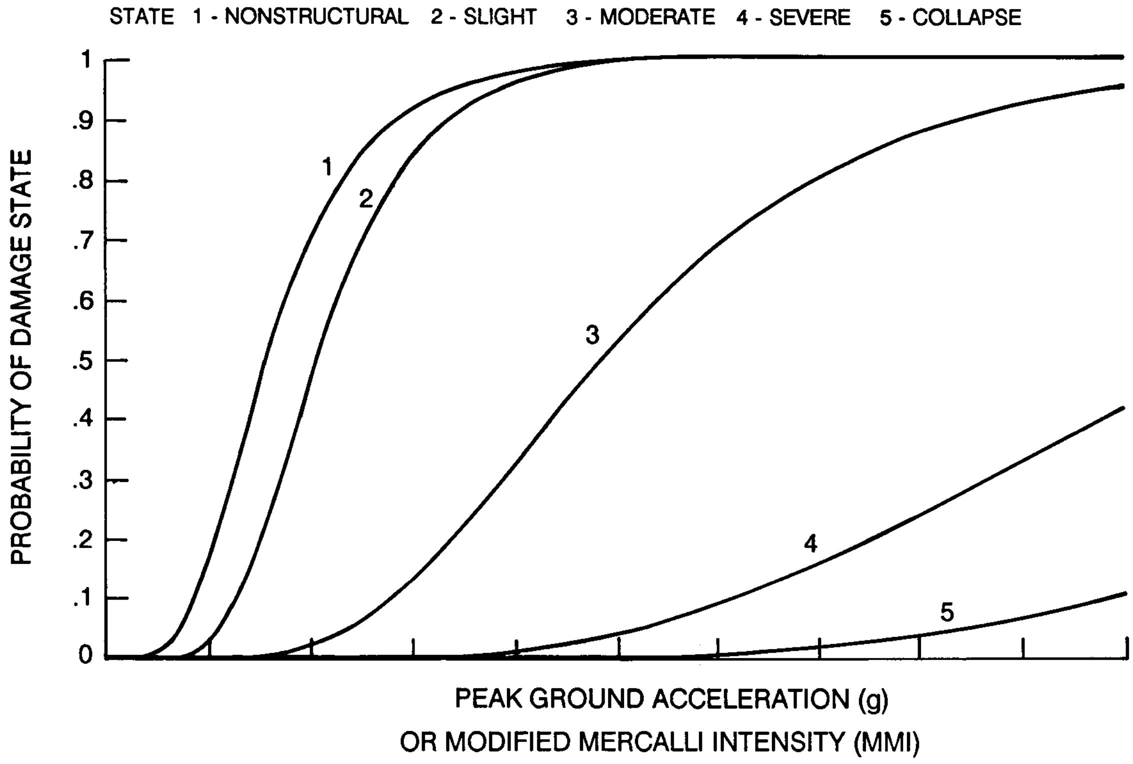

FIGURE 4-3 Example of fragility curves. Source: Kircher and McCann (1983).

design and construction, and the ATC-13 report provides a method for combining adjacent columns in a DPM to reflect the dispersion introduced when good, average, and above-average construction are lumped together. The panel recommends the development of new DPMs that incorporate this range of different qualities of construction.

For common building types, loss ratio curves calculated from the DPMs in ATC-13 are very close to the corresponding curves developed by the ISO. For less common buildings (e.g., tilt-up wall construction) for which there are only limited data, the differences in loss ratios expressed by the ISO and ATC-13 methods are within the range of uncertainty in the data. The best use of the ATC-13 DPMs, in the panel's view, is for building types for which there are no ISO curves.

Both the ISO loss ratio curves and the ATC-13 DPMs are intended primarily for use in California. The question then is: How should motion-damage relationships be developed for use in loss estimates for other areas? One answer lies in using expert opinion to modify the California-based information for the types of buildings found in the area to be studied. Analysis of some selected buildings can assist by indicating the general level of seismic resistance of generic examples of building types in relation to the resistance of the buildings forming the data base.

A Look to the Future

It is clear that there are major gaps and uncertainties in the state of the art for evaluating damage from an earthquake. Improvements in this situation can come about only by systematically collecting data from actual earthquakes. More effort should be devoted to this purpose, not only for earthquakes in the United States but also for earthquakes in other countries. In all such future studies, the distribution of damage should be documented—not just the mean loss ratios, and not just by documenting interesting or dramatic individual failures in a reconnaissance overview.

There has been an effort to develop and use empirical relations connecting damage directly to magnitude and distance from an earthquake (Steinbrugge et al., 1984). This approach bypasses the need to evaluate the intensity of ground shaking at sites, and avoids difficulties in using MMI. Initial efforts to establish such relations are under way using data from earthquakes in California. This is an interesting idea and should be pursued, but there are obvious limitations and difficulties. First, different relations will be necessary for different soil and topographic conditions. Second and more important, different relations will be required for different regions of the country according to variations in attenuation of motion with distance.

LOSSES ASSOCIATED WITH BUILDINGS

One form of loss—the cost of repair—has already been discussed in the previous section. The total cost of repair may be obtained by simple summations, such as:

$$\sum_{\text{all building categories}} (\text{dollar value in each category}) \times MDR_I,$$

or

$$\sum_{\text{all building categories}} (\text{average dollar value}) \times (\text{number of buildings}) \times MDR_I,$$

where MDR_I is the loss ratio (or mean damage ratio) for the intensity of the scenario earthquake. Such summations are made for subareas of constant intensity and are then combined.

Considering uncertainties that will inevitably exist in the inventory and the additional uncertainties in motion-damage relations, the accuracy of the estimated loss for a given scenario is not great. A prudent claim would be accuracy to within a factor of 1.5 for the aggregation of single-family, wood-frame California dwellings, 3 for commercial, industrial, and institutional buildings, and an order of magnitude (factor of 10) for an area with no recent earthquake history.[2] However, even such uncertain estimates are still very useful for hazard reduction efforts and emergency planning.

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[2] These expressions of uncertainty indicate the panel's judgment as to the accuracy with which losses can be estimated. A precise statement about the meaning of these ranges is not possible with the present state of the art, but the following example indicates a reasonable interpretation:

- Statement: "Uncertain by a factor of 3."
- Interpretation: Best estimate, 1,000; high estimate, 1,800; and low estimate, 600.

The estimation of other types of losses–casualties and homelessness–is more complex and difficult.

Casualties

Of all the losses to be estimated, deaths and injuries are perhaps the most important to governmental organizations. Protection of life is a primary function of government and a prime incentive for undertaking hazard reduction. Estimates of casualties are desired for different times of day–typically mid-day, at night, and perhaps at a commuting hour–and sometimes for different seasons of the year.

Unfortunately, the ability to predict casualties is not as good as in the case of property loss. Data on which rational, systematic estimates can be made are very sparse. The early NOAA-USGS studies generally used historical rates of casualties per unit of populaton for wood-frame dwellings and estimated rates for other types of construction, or used city-wide casualty rates from previous earthquakes applied to the population as a whole, adjusted up or down based on changes in construction practice. These estimates were in effect crude extrapolations of the limited data available, primarily from California earthquakes.

A method specifically intended to estimate life safety risk factors for most of the ISO construction classes was devised by McClure et al. (1979) and applied to the problem of prioritizing engineering studies for buildings owned by the State of California.

More recently (e.g., in the ATC-13 project) the tendency has been to relate casualties to levels of damage. For example, Table 4-3 gives casualty rates tied to the damage states described in Table 4-2. These rates are then multiplied by the estimated numbers of people in buildings of varying classes.

This information is based on limited data plus considerable judgment. This does represent a rational approach to estimating casualties, and the panel recommends use of this method combined with careful judgment and comparison with historical data, where comparable cases pertain. It is essential that it be used with a DPM that reflects the considerable dispersion of damage among buildings of any one type, and the recommendations in ATC-13 for noting variations in construction quality should be followed.

TABLE 4-3 Injury and Death Rates in Relation to Damage[a]

Damage State	Central Damage Factor (percent)	Fraction Injured		Fraction Dead
		Minor	Serious	
1	0.0	0	0	0
2	0.5	3/100,000	1/250,000	1/1,000,000
3	5.0	3/10,000	1/25,000	1/100,000
4	20.0	3/1,000	1/2,000	1/10,000
5	45.0	3/100	1/250	1/1,000
6	80.0	3/10	1/25	1/100
7	100.0	2/5	2/5	1/5

[a] Estimates are for all types of construction except light steel construction and wood-frame construction. For light steel construction and wood-frame construction, multiply all numerators by 0.1.

SOURCE: Applied Technology Council (1985).

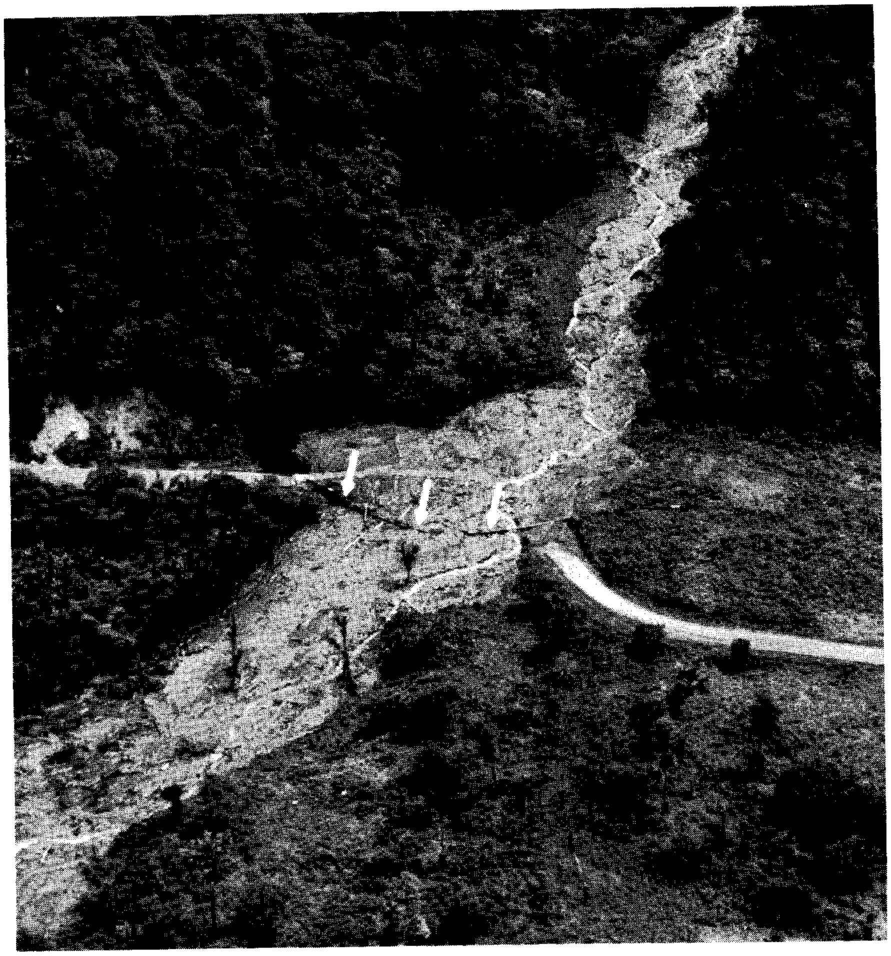
It is evident that estimates of casualties will be very crude and uncertain, and this uncertainty should be represented by, for example, giving ranges of estimates, along with providing the best estimate figures.

Homelessness

Estimates for the number of people requiring shelter by public agencies are also important for planning postdisaster operations. It is even more difficult to make such estimates, partly because data are scarce and partly because potential need is a function of weather conditions and the ability and inclination of the population to find their own shelter, such as with friends and relatives.

The NOAA-USGS studies used a 50 percent dwelling damage ratio as an indicator of the need for alternative shelter. The most complete effort at systematic estimation of homelessness is by Gulliver (1986), who suggested a 20 percent damage ratio as the threshold point past which homelessness results. Clearly, great judgment is required when estimating homelessness, and any estimate will involve a high level of uncertainty.

Estimates of casualties and homelessness should be regarded as having an order of magnitude (factor of 10) uncertainty, although it is possible to provide a tighter range of estimates when a study is restricted to a few well-understood classes of construction. These obviously are both matters for which far more data from actual earthquakes are required to advance the state of the art.



An example of the effects of landslides and debris flows triggered by the March 5, 1987, earthquakes (M 6.1 and 6.9) along the eastern flank of the Andes in north-central Ecuador. Destruction can be seen of the Trans-Ecuadorian oil pipeline (indicated by arrows) and adjacent highway by a debris flow issuing from a minor tributary of the Coca River. *Photo courtesy of R. L. Schuster.*

5

Collateral Hazards

Collateral hazards include fault ruptures, landslides, liquefaction, tsunamis, and seiches. As noted in an earlier section, collateral hazards can cause very significant losses. For example, most of the losses experienced in the Alaskan earthquake of 1964 resulted from collateral hazards, with landslides causing major property loss and tsunamis causing 119 of the 131 fatalities (National Research Council, 1972).

In principle, the overall method for predicting losses that might result from these hazards is much the same as that for losses caused by shaking of facilities. The first question is: How extensive and severe might collateral hazards be? For example, how large an area might be affected by landsliding, and how far and how rapidly might the earth move? These are questions for earth scientists, such as geologists.

The next question is: What damage and losses would result? These primarily are questions for engineers. Where structures are impacted directly by severe collateral hazards, losses may be quite large. Sometimes the effect of a hazard may be indirect. For example, the Hebgen earthquake in Montana in 1959 triggered a landslide that blocked the Madison River, and a lake began to form behind this earthen mass. Considerable effort was expended to alleviate concern about potential downstream flooding when this potentially erodible "dam" eventually overtopped.

FAULT RUPTURE

A surface fault rupture involving several feet of movement will cause major damage (50 percent loss ratio or greater) to almost all houses or small structures sited directly on the fault, and generally even greater damage to larger structures. However, well-built buildings located within only a few feet of a well-defined fault rupture may experience little or no damage. Losses to buildings directly attributable to surface rupture usually are a small fraction of total losses associated with an earthquake, and can be predicted with satisfactory accuracy once the path of the rupture is defined. In the eastern United States, it appears that potential faults are deeply buried and hence fault rupture probably does not extend to the surface. Hence this particular hazard generally can be ignored in this large portion of the country.

LANDSLIDES AND LIQUEFACTION

Landslides and liquefaction are consequences of ground shaking. A rational procedure for evaluating liquefaction and landslide-caused losses as a result of a scenario earthquake is described in ATC-13 and involves the following steps:

1. Identify soil, geologic, and topographic conditions potentially susceptible to such failures as a result of an earthquake.
2. Select relations expressing the likelihood of failure, or the fraction of susceptible area expected to fail, as a function of the intensity of ground shaking.
3. Select additional relations giving loss ratios for buildings and other facilities located at failed areas.

These steps parallel those for the direct effect of ground shaking upon buildings (Figure 1-2).

Identification of areas where these hazards may occur is a major inventory-type problem. The USGS has prepared, or helped prepare, detailed geological hazard maps for several metropolitan areas (e.g., Borcherdt, 1975; Youd et al., 1978; Ziony 1985), and is collaborating in the development of such maps for additional areas. Generally these maps showed areas within which there is a significant likelihood that landsliding or liquefaction might be triggered by an earthquake, and it is not necessarily expected that actual hazards will occur in all such areas or over all of a given area. Preparing a good map of collateral geological hazards is a time-consuming and expensive task.

If these maps are not already available, it is necessary to construct an approximate hazards map using the expertise of experienced local geotechnical engineers and geologists. ATC-13 summarizes the general principles to be followed, and more specific guidance is available in a recent compilation of papers by USGS (Ziony, 1985) and a report on liquefaction by the National Research Council (1986).

Liquefaction

The word *liquefaction* has been used to cover several different types of phenomena associated with the increase in pore water pressures in cohesionless soils during earthquake shaking, with a resulting decrease of strength and/or stiffness. One common manifestation is lateral spreading of nearly level ground toward adjacent dips or other low points. Such lateral spreading can disrupt roadways, canals, pipelines, and so on, and will also damage buildings in the area affected by the spreading.

Liquefaction can also cause more dramatic flow slides from steeper slopes, which occurred at the lower Van Norman Dam during the 1971 San Fernando earthquake (Seed et al., 1975), at mine tailings dams in Chile in 1965 (Dobry and Alvarez, 1967), and at the waterfront in Seward, Alaska in 1964 (Seed, 1973). Obviously such slides are extremely damaging both to any structures on the slide area or in the path of the slide.

Still another manifestation of liquefaction is the appearance of sand boils (small volcanoes emitting sand and water) on the surface of level ground. Where such sand boils occur, there can be excessive settlements of facilities. There may also be large differential horizontal movements between only slightly distant points on the surface, resulting in damage to highway, pipelines, and so on.

Liquefaction has been observed repeatedly during earthquakes in California, but it has also been observed elsewhere. An enormous area was affected by massive liquefactions during the 1811–1812 New Madrid, Missouri earthquakes, and the phenomenon was very evident during the 1886 Charleston, South Carolina earthquake. Liquefaction is a potential problem in any area where a loss estimation is being made.

The liquefaction hazard maps are based on general indicators of liquefaction susceptibility: geological age, the manner in which cohesionless soil is deposited, and the depth to the water table. Detailed procedures involving drilling and sampling have been developed for evaluating the liquefaction susceptibility of specific sites; such efforts are beyond the scope of a loss estimation study, although it may be possible to make good use of pre-existing data to supplement geological information. Approaches developed for California to identify liquefaction susceptible areas (Youd and Perkins, 1978) can be used, with proper judgment and knowledge of local conditions, to guide preparation of approximate maps for areas in other parts of the country.

ATC-13 contains relations giving estimated fractions of liquefaction susceptible areas experiencing different damage states (i.e., degrees of liquefaction) as a function of MMI. These were prepared using expert opinion, and are generally applicable throughout the United States. A very recent paper by Youd and Perkins (1988) presents a method for mapping liquefaction severity index (LSI), which is related to the extent and severity of liquefaction phenomena within liquefaction susceptible soils. The specific relations suggested in this paper are derived from experiences in California, and cannot be extrapolated directly to other parts of the country.

The same ATC-13 report also gives damage ratios for the losses to buildings affected by liquefaction. These clearly are engineering judgments, but they do provide some guidance. Combining this damage information with maps of liquefaction susceptible areas and estimations of extent and severity of liquefaction provides property loss estimates from these collateral hazards. It is essential to keep in mind that different manifestations of liquefaction (e.g., lateral spreading and sand boils) have quite different implications concerning damage.

This method is untried and must be used with caution and judgment and tailored to local situations, but it does permit systematic evaluation of potentially important losses.

Landslides

Here *landslides* is used to cover all permanent earth movements other than those involving saturated cohesionless soils.

In a very comprehensive review of earthquake-induced landslides to date, Keefer (1984) reviewed 40 earthquakes worldwide and ranked the abundance of different types of landslides. He listed disrupted soil slides as very abundant; soil slumps, soil lateral spreads, soil block slides, and soil avalanches as abundant; and rapid soil flows as moderately common. Of these types of landslides involving soils, only soil lateral spreads and rapid soil flows most likely involve liquefaction or failure of sensitive clays. The most notable example of failure of sensitive clays in this country occurred in Anchorage, Alaska in 1964 (Seed, 1973). Technical methods for assessing specific sites are available, but generally are beyond the means of a broad area loss estimate study. Since a combination of very sensitive clay and very strong shaking must be present if such failures are to occur, local geotechnical and geological experts should be able to decide whether or not this particular problem is present.

Soil falls, disrupted soil slides, and soil avalanches can occur as failures of dry, cohesive or cohesionless soils (Keefer, 1984) and were assessed as particularly common to abundant in the 1811–1812 New Madrid (Missouri) and 1906 San Francisco earthquakes. Likewise, landslides in cohesive soils are not restricted to sensitive clays, as shown by Keefer's historic review. Soil slumps, for example, have been at least moderately common in many earthquakes where sensitive clays do not exist.

Landslides in rock (e.g., rockfalls and debris flows) are expected only in steep terrain, in rock formations experiencing a loss of strength during ground shaking. It is very difficult to determine, even with the most careful testing and evaluation, whether or not a slide is likely, in relation to ground-shaking intensity, at a given rock site. Thus it is necessary to rely very heavily on past experience and judgment. ATC-13 contains results from expert opinion concerning the probability of such events. The historical review of 40 worldwide earthquakes by Keefer (1984) formed the basis for developing methods to identify seismically induced landslide susceptibility. These methods have subsequently been applied to several California metropolitan areas, including San Mateo County (Wieczorek et al., 1988) and the Los Angeles Region (Wilson and Keefer, 1985). Of the 40 earthquakes in the review, only 10 were from California. At least a half dozen were from other regions in the United States, including Alaska, Hawaii, Missouri, Montana, South Carolina, and Washington, with the rest of the historical earthquakes from other parts of the world having a variety of geologic and climatic conditions.

ATC-13 also provides estimates for the likelihood of damage to facilities, given that landsliding occurs—again from expert opinion. The warning in the last paragraph under liquefaction applies even more to landslides in rock. Locally steep rock slopes, particularly in closely jointed and weakly cemented rocks, are highly susceptible to seismically induced rockfalls and rockslides as noted by Keefer (1984).

These slopes need not be particularly high; a steep slope 10–20 m high could generate a damaging rockfall. Many metropolitan areas are naturally hilly and in combination with highway cuts, hillside excavations for building foundations create sufficiently hazardous conditions for rockfall and rockslides during earthquakes. Within the United States, Los Angeles, Memphis, Portland, Salt Lake City, San Diego, San Francisco, and Seattle are a few examples of large metropolitan areas with recognized potential for seismically induced landslides involving rock.

TSUNAMIS

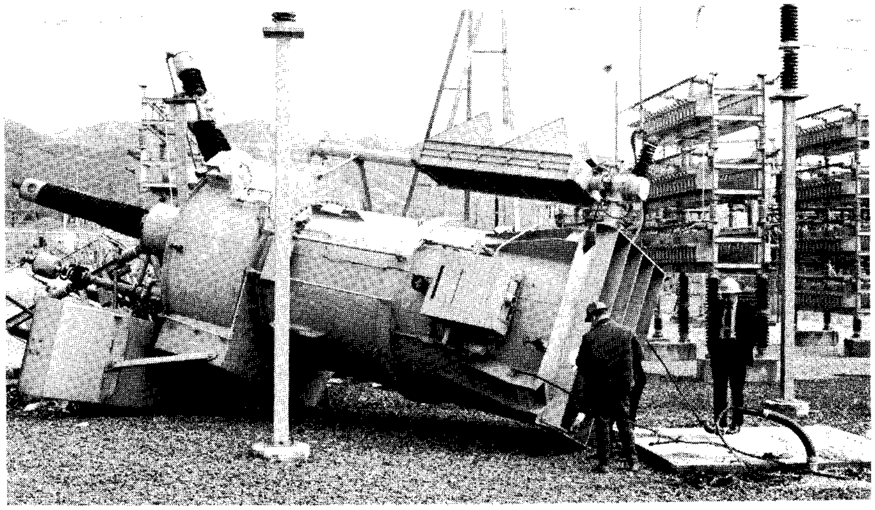
Tsunami inundation areas for the West Coast of the United States, including Alaska and Hawaii, are available in the form of FEMA flood maps (FIRM or Flood Insurance Rate Maps). For the East Coast, the potential hurricane storm surge exceeds possible tsunami heights, and tsunami hazard zones are thus of less importance and are not plotted on FIRMs. Other maps by USGS or the U.S. Army Corps of Engineers are also available and show the extent of expected tsunami run-up for the West Coast. A mean recurrence interval for the tsunami of 100 or 500 years, or both, is commonly used as a basis for developing these maps.

Even though tsunami hazard maps are available, there are two basic difficulties to overcome in estimating losses. First, as with ground failures, one must assess the degree of damage to various structures that might be caused by a range of water heights and velocities. All structures located within the shaded tsunami run-up zones on a map are not expected to be subjected to the same effects. Second, the tsunami map obtained will generally be predicated on a variety of causative earthquakes that may be located thousands of miles away, and thus tsunami losses may be unrelated to the losses associated with a local earthquake scenario. Generally, the major tsunami risk in California, Oregon, Washington, and Hawaii is posed by distant earthquakes, such as large Alaskan or Chilean events. In southern Alaska, a local earthquake could cause a tsunami, and the earthquake and tsunami losses might thus be combined in a particular scenario.

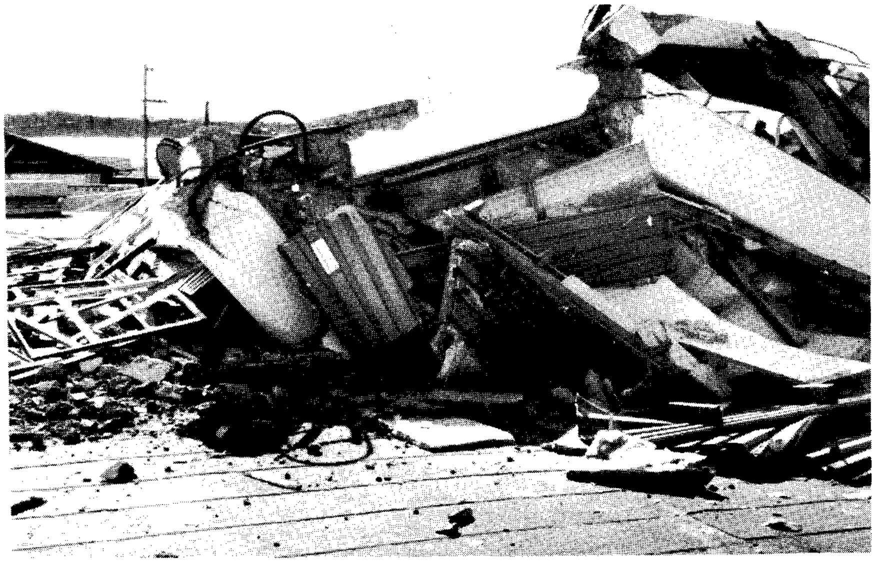
SEICHES

Here *seiches* refers to waves induced in lakes, reservoirs, and so on as a result of ground shaking (or perhaps because of permanent tectonic movement of the underlying earth). If these waves are of sufficient amplitude, facilities along the waterfront may be damaged and there might be overtopping and thus damage to any earth dam retaining a reservoir.

A specialized study is needed to determine whether or not there might be a problem and if so the extent of it. Fortunately, seiches are usually not a problem.



Electrical equipment that is not anchored securely to the foundation can move and fall over, as happened to this unit during the 1971 San Fernando earthquake (M 6.6). This earthquake did extensive damage to electric power facilities, freeway bridges, and water and gas distribution systems. *Photo courtesy of G. Housner.*



Collapse of an airport control tower in Anchorage, Alaska during the 1964 earthquake (M 8.3–8.6). One man was killed in the collapse and one was injured. All air traffic control and advisory services were disrupted in the Anchorage area due to damage to telephone, interphone, and teletypewriter communication lines. *Photo courtesy of G. Housner.*

6

Damage and Losses to Special Facilities and Urban Systems

The methods used to estimate losses for the general population of buildings must be modified for application to lifelines, facilities with essential emergency functions, or facilities with a potential for very large losses.

LIFELINES

Lifelines (or utilities and infrastructure systems) include railroad, airport, motor vehicle, water, telephone, electricity, natural gas or oil pipelines, sewage, port and airport, and communications services. The words *systems* and *services* are central to the distinction between the loss estimation process for lifelines as compared to buildings.

Service outages are almost always a prominent concern addressed by lifeline loss studies. Property losses are also important, but casualties associated with damage to lifelines usually are small. A lifeline, such as a water or electrical utility's facilities and functions, must be analyzed as a *system* rather than as separate, unrelated structures.

Securing the active cooperation and support of local lifeline owners, operators, and regulators is the key to producing a satisfactory loss estimate. An understanding of how the system operates is essential.

The first step in the analysis of lifelines is to estimate the probability that components of the system will fail. Examples of components would be bridges in highway routes, switchyards and transformer stations in power systems, and pumping stations in water and sewage systems. The estimation of losses to the individual components of a system has a less extensive historical loss experience to support the development of construction class motion-damage relationships than with buildings. The most ambitious attempt to date to develop classes that include nonbuilding structures is ATC-13, in which some 30 classes are related to lifelines.

The panel believes that the DPMs in ATC-13 provide the best available guidance, especially for bridges, although adjustments for local conditions will generally be necessary. ATC-13 DPMs should be used with a knowledge of the specific definitions of the classes. For example, a DPM that was devised for the case of seismically anchored electrical equipment should not be applied to a case where the equipment is unanchored.

Buried pipelines are more vulnerable to collateral hazards such as fault ruptures, landslides, and liquefaction than they are to ground shaking. The probability of failure of such a pipeline under these collateral hazards will depend on the detailed characteristics of the ground movement and the material, age, depth of burial, and wall thickness and diameter of the pipeline. There are examples of successful pipeline performance as well as failures for each of these collateral hazards. For any specific pipeline and detailed characteristic of ground movement, an evaluation of pipeline performance can be made. However, such detailed evaluations are beyond the feasible scope for a large geographic loss estimation study that includes many such pipelines. For these studies, the probability of failure of buried pipelines should be treated as being rather high (greater than 50 percent) wherever collateral hazards are postulated to occur.

Similarly, with the exception of bridges, which are potentially vulnerable to both effects, highway and railway networks are also more vulnerable to collateral hazards than they are to ground shaking. The probability of failure of links in such networks due to collateral hazards should be treated similarly to that described above for buried pipelines.

Once the probability of individual components failing has been estimated, the next step is then to evaluate the influence of the failure of components or segments on the performance of the system, as a whole. If analytical models exist for the system (utilities will often have such models), the effect on overall performance of the loss of some components can be estimated readily. Lacking any available system-wide models, expert opinion based on available data must be used to estimate the outages that might be expected. In either case, the result is a scenario describing the state of the lifeline; that is, its ability to provide service following the earthquake.

In addition to degradation in system-wide performance, there may be localized outages. For example, pipes in local distribution systems may fail as a result of ground shaking or ground failures, and streets may become clogged by debris. These local failures contribute to the overall problem of restoring service.

The time needed to restore service is an important factor in planning for disaster response. This is, in part, a matter of the time required to bring components back to a serviceable condition (e.g., to fix breaks in pipelines or to inspect bridges). The ATC-13 report contains time-to-restore-service matrices for a number of lifeline components. Restoring service also depends on the emergency response capability of the lifeline operator or of other emergency response agencies. A utility with an earthquake-resistant radio system, personnel who undergo annual earthquake exercises to test their ability to carry out preassigned tasks, and back-up plans for using emergency bypasses should be much more able to contain the impact of earthquake damage than another utility that does not have these capabilities and experiences the same damage. Considerations such as these must be handled on a case-by-case basis after evaluation of the utilities' emergency preparedness.

Loss estimation studies have seldom incorporated lifelines into the study to the same extent as building losses. Lifeline loss estimation methods are not as mature as for building loss estimation, and the problems are very complex. There has been considerable research into methods for evaluating the performance of interconnected systems in probabilistic terms, but as yet these sophisticated methods have not been used in conventional, multipurpose, regional-scale loss studies. The panel encourages more systematic and sophisticated studies of losses to lifeline systems, partially for the purpose of aiding in the maturing of lifeline loss estimation. However, additional damage statistics will accumulate only slowly, because so many factors affect the behavior of components in lifeline systems.

FACILITIES WITH ESSENTIAL EMERGENCY FUNCTIONS

In general-purpose loss estimates, the main focus of this study, special attention must be given to those facilities most essential to emergency response, such as fire stations, emergency operations centers, and hospitals. The key question is: How well will these facilities be able to perform after an earthquake?

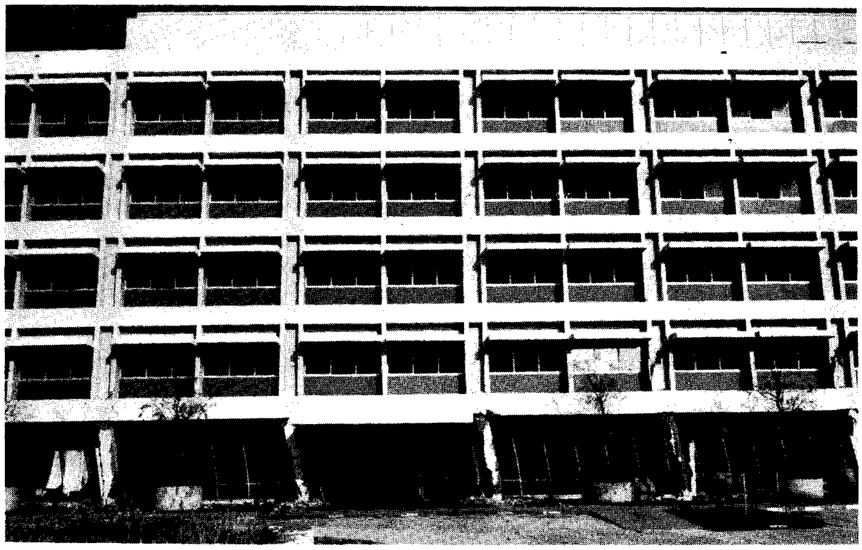
Obviously, if such facilities suffer severe structural damage, their usefulness will be negated or greatly impaired. However, even if there is little or no structural damage, the facility may be unable to function effectively if nonstructural damage causes critical equipment to be dislodged or overturned, or if essential or dangerous chemicals have been thrown down from shelves, or if lifelines services are interrupted.

Nonstructural damage is significant because it is generally more widespread than structural damage. Even a moderate level of ground shaking (such as VI or VII on the MMI scale) can cause nonstructural damage, such as overturned gas cylinders or water heaters and the release of flammable or toxic gas. The inventory task of field surveying nonstructural characteristics for the building population at large has yet to be attempted in a large-scale study, but this effort should be undertaken for the smaller number of essential, emergency function facilities that are within the scope of a large-scale study.

During a loss study, it generally is necessary to walk through each essential facility allowing sufficient time to assess the likelihood of severe structural damage, but it also is essential to ascertain whether critical equipment and supplies have been adequately secured, and whether back-up resources have been arranged to deal with utility outages. This is labor intensive work and requires earthquake engineering expertise, but these are unavoidable costs.

Undertaking a detailed structural analysis of such facilities is generally beyond the scope of a loss study. However, it may be desirable to examine structural drawings and to utilize a rapid assessment method. Critical evaluation of these methods is beyond the scope of this report.

Even though each emergency facility is inventoried, the problem of potential liability to those involved with this work may make it desirable for a number of such facilities to be grouped when stating expected losses. That is to say, the result is a scenario describing the functionality of the emergency response system as a whole and not the functionality of individual facilities.



The flexible, first-story of this hospital building was overstressed during the 1971 San Fernando earthquake (M 6.6). Although designed in accordance with the 1970 building code, this reinforced-concrete structure was so severely damaged that it was torn down. The intensity of ground shaking was much greater than the hypothetical intensity upon which the code requirements were based. *Photo courtesy of P. C. Jennings.*

Aerial view of collapsed hospital buildings in Sylmar, California. The older, weaker buildings collapsed and the newer, stronger buildings survived with only minor damage during the 1971 San Fernando earthquake (M 6.6). *Photo courtesy of G. Housner.*

The ATC-13 report solicited from experts the DPM for mean percentage property loss (termed damage factor by ATC-13 and generally called damage ratio by others) versus the MMI for six classes of equipment (i.e., residential, office, electrical, mechanical, high technology and laboratory, and vehicles). The validity of these relatively gross groupings is unknown and untested at present, although considerable variability is known within these types of equipment. For example, in the mechanical category, many pumps are routinely bolted to concrete slabs and are relatively earthquake resistant, even where earthquakes are not specifically considered in design. Also within this overall category of mechanical equipment is air-handling equipment mounted on springs, and these items are usually quite vulnerable to earthquakes except where special seismic measures are taken. The six classes of equipment analyzed by ATC-13 are also not all-inclusive.

The equipment DPMs were not directly used in the ATC-13 functional loss estimation process. Instead, experts were asked to assign recovery times to the damage states of Table 4-2 (e.g., loss damage state 1 = no damage) for 60 socioeconomic classes of building use. For the class defined as health care services, for example, each expert had to decide how a given damage state (that now included structural plus equipment damage in its definition) affected the facility's functionality in terms of time to restore service to 30 percent, 60 percent, and 100 percent. Loss of function resulting from lifeline service outages were included as a separate step. To be valid, these relationships (of MMI to equipment damage, and of combined structural and equipment damage state to functional loss) must be defined more specifically than to say they represent "typical" California practice.

It should be clearly recognized that there is less certainty and less maturity in such techniques for estimating functional loss than for estimating property loss. For essential facilities, individual field visits rather than reliance on general relationships are recommended.

Considerable potential exists for improving estimates of the performance of essential facilities through research into the earthquake performance of nonstructural items and identification of typical nonstructural conditions in different parts of the country. While the state of the art of quantitative nonstructural loss estimation is not well developed, guidance for identifying and reducing nonstructural vulnerabilities is available in works such as those by McGavin (1981, 1986), Reitherman (1985, 1986), Stratta (1987), and the Veterans

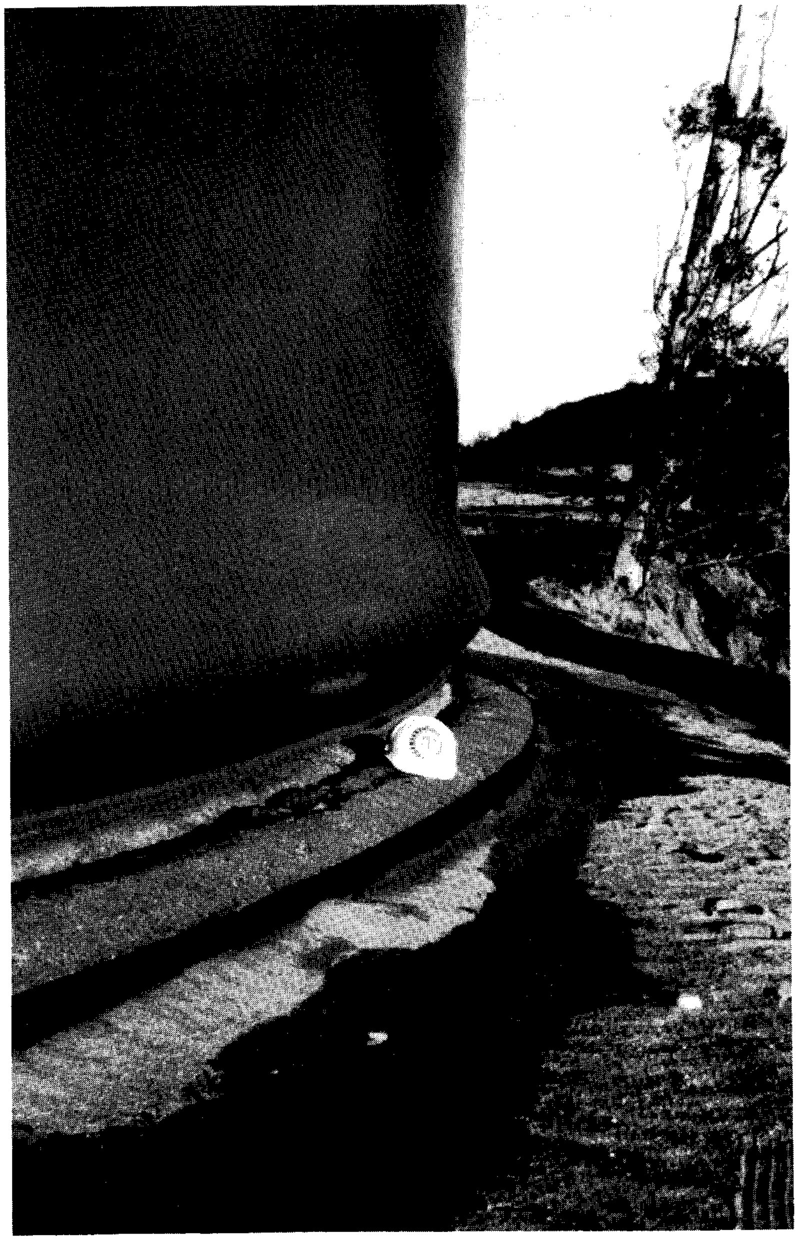
Administration (1976, 1981). For emergency planning purposes, references documenting functional losses (e.g., Arnold and Durkin [1983] concerning hospitals) or other reports in the postearthquake reconnaissance and research literature are useful for pointing the way toward improving emergency response capabilities, even though quantitative response dysfunction can only be very approximately predicted.

FACILITIES WITH A POTENTIAL FOR LARGE LOSS

In this category are large and densely occupied buildings and other facilities such as tank farms, refineries, dams, liquefied natural gas (LNG) plants or storage areas, chemical plants, nuclear plants, and pipelines containing hazardous materials. The characteristic feature of these facilities is that failure could cause an enormous number of casualties as well as very large property losses.

Except possibly for large and densely occupied buildings, there may be only a few of these facilities in a given study area. Thus, the loss estimator cannot take advantage of averaging out uncertainty in performance over many facilities, as can be done for the ordinary building stock. Unless the loss attributable to a facility can be stated with great confidence, including it may completely bias the projected overall losses for the region. Since the loss from an individual building or other facility cannot be estimated reliably except through very detailed and expensive analysis, it follows that possible losses from such facilities should not be quantitatively included in the overall estimated loss.

Obviously, however, the existence of such potentially hazardous facilities cannot be ignored. They should be highlighted in the inventory, and the cognizant regulatory bodies should be urged to require that detailed studies be made. A large-scale multipurpose study can educate local officials and staff personnel about the potential threat and the need to map the location of such facilities.



Damage to a liquid storage tank during the 1971 San Fernando earthquake (M 6.6). The sloshing of the fluid contents overstressed the wall of the tank. Sometimes such overstressed tanks collapse and combustible contents ignite. ***Photo courtesy of P. C. Jennings.***

7
Indirect Losses

Indirect losses follow from the direct effects of an earthquake. They may be very important, but are difficult to evaluate.

FIRE

Most loss estimates in the United States have not included losses from fire in a formal, quantitative way. While fire has not been a major factor in recent earthquakes in the United States, more than 100 ignitions occurred in the 1971 San Fernando earthquake, and a shopping center fire was the single largest loss in the 1984 Morgan Hill, California earthquake (M 6.2). Thus, the specter of fire loss following earthquakes, similar to the 1906 San Francisco earthquake, is always present.

Scawthorn et al. (1981) and Oppenheim (1984) have made starts toward a formal procedure for evaluating expected losses from fires. The discussions of this topic in ATC-13 and Steinbrugge and Lagorio (1982) are also useful. More recently, Scawthorn (1987) has provided estimates of losses due to fire following earthquakes in the Los Angeles and San Francisco regions. Data for the initiation of fires following earthquakes in the United States, and especially for the different conditions in Japan, exist. Models can include consideration of time lags in reporting fires and responding to them as well as weather conditions to estimate the possible spread of fire.

However, such models should be used with caution in a generalized loss study because major work remains to advance the state of the art. Inherently, the problem is very complex. A recent reminder that the state of the art of forecasting earthquake-caused fires is poorly developed is provided by the work of Hansen et al. (in progress) on the 1906 San Francisco earthquake. A much larger number of ignitions has been documented than was previously reported, and other previous data, concerning casualties especially, are also being significantly revised.

Possible losses from fire, and the implications to disaster response planning, certainly must be recognized. Property losses from fire are of great concern to the insurance industry, and attempts to quantify possible fire-related losses will certainly continue. From the emergency planning standpoint, information concerning the expected performance of the water supply, communication, gas distribution, and highway and street systems can be used as a basis for devising emergency response plans. Postearthquake fire modeling is also useful to identify general areas of high conflagration potential (e.g., concentrations of wooden buildings) or special risk factors unique to the postearthquake situation (e.g., telephone, transportation, or water system outages).

RELEASE OF HAZARDOUS MATERIALS

Concern about potential releases of hazardous materials was emphasized in the user workshop. Laws in many states and communities have required that an inventory of hazardous substances be maintained at the local level, and Title III of the Superfund Amendments and Reauthorization Act of 1986 imposed nationwide inventory requirements. Lacking legal sanction for having such an inventory, it may be impossible to secure the cooperation of industrial facilities in preparing one.

In general, there is only a limited amount of data from earthquakes upon which to judge the likelihood that releases will occur, as a function of ground-shaking intensity. The manner in which substances are contained will be the major factors affecting the probability of releases. For some general types of components, such as tanks, considerable earthquake performance data and analytical or test findings are already available. Even here, however, this is little direct information as to the likelihood of a release given that a tank has overturned. Development of methods for evaluating the seismic resistance of a range of storage arrangements is an important task for the future.

ECONOMIC IMPACTS

Many economic impacts are associated with earthquake damage. These include loss of production capacity in individual manufacturing facilities, loss of income to commercial enterprises where functionality is destroyed or impaired, the loss of jobs, economic impacts on other undamaged businesses within a region, and losses to industry and commerce located outside the affected region but linked economically to it. In some instances, economic benefits may be associated with an earthquake, such as an influx of federal aid and the creation of new types of jobs. The need to undertake such an analysis was a major motivation for FEMA's sponsorship of the ATC-13 effort.

If such losses are to be considered, the inventory must include considerable information. The economic function of buildings must be identified, and commercial and industrial activities categorized. The 35 basic social function categories in the ATC-13 report are reasonable. However, given the inadvisability of assigning buildings to construction classes based only on socioeconomic data, the panel estimates that about 25 to 50 percent more effort would be needed to include this level of classification of uses in an inventory. In addition, considerable effort by economists will also be needed to develop the economic models that link various commercial and industrial activities inside and outside the region.

The panel recognizes the potential value of analyses of this type, and encourages them. It recommends that a pilot study of this type be added to a future loss estimation study.

8

Rapid Postearthquake Loss Estimates

In establishing the scope of this panel's study, FEMA cited the potential value of being able to estimate losses quickly after an actual earthquake, as a basis for planning disaster response and financial assistance. The panel was specifically asked whether cruder techniques of rapid loss estimation might be developed for this purpose.

An early study by Algermissen (1978) was inspired by this desire for a technique to evaluate earthquake losses rapidly. It resulted in a method for estimating earthquake losses that was much the same as the NOAA-USGS method discussed in this report, and it assumed that the inventory was reasonably up-to-date.

The inventory and other information assembled for any loss estimate may be used very quickly once the magnitude and location of an earthquake are established, ***provided*** the inventory is current, the computer software is current, and the computer is operating and available. If this approach were to be tried, the data bank and computer software must be maintained in an active condition outside all potentially affected areas. In addition, the crudeness of loss estimates based on the best of today's technology must be kept in mind.

Reports from the affected area based on field reconnaissance usually will provide a more accurate picture of the extent of losses than the best of theoretical loss estimate calculations, and obviously this will be even more true for the cruder estimation techniques.

The panel recommends that low priority be given to developing approaches that rely on projections rather than on field reconnaissance and actual damage reports after earthquakes.

9

Conclusions and Recommendations

SUMMARY GUIDELINES FOR MULTIPURPOSE, LARGE-SCALE EARTHQUAKE LOSS ESTIMATES

This chapter presents the panel's conclusions and recommendations for conducting general loss estimate studies of the type currently being funded by FEMA and primarily intended for use by local and state governments for disaster response and mitigation planning, and to aid in the formulation and implementation of near- and long-term strategies for earthquake hazard reduction.

Study Preparation and Planning

The objectives and scope of a study must be defined clearly and early in a study. Potential users for the study must be identified and plans made for the ultimate dissemination and utilization of the report. Specific plans should be made for the involvement of key local and state personnel throughout the study.

One very important decision at this stage concerns the scope and detail of the inventory and the form in which it will be prepared. Discussions should be held with a spectrum of potential users for the inventory, to identify interest in and commitment to developing and maintaining an inventory in a computer-based format.

Scenario Earthquakes

Earthquakes selected for scenarios should be relatively probable and yet damaging. Using too large and improbable an earthquake may lead to a loss of credibility in the loss estimate or create a feeling of hopelessness in dealing with the high-loss estimate. No standard exists for selecting scenario earthquakes. For the more seismic portions of the country, use of the historical maximum earthquake is often reasonable. For less seismic areas, probabilistic hazard analysis is useful. There also is no standard for the choice of a mean recurrence interval for a scenario, but intervals of as long as 1,000 years may be reasonable for disaster response planning, depending on the intended use. As in seismic design, the more essential or potentially hazardous the facility or system, the longer the recurrence interval that is considered. It is desirable that at least a rough indication of the probability of occurrence be attached to all scenario earthquakes to convey to users and to the public some indication of the likelihood of the events.

Despite the problems associated with the use of Modified Mercalli Intensity (MMI) scale to prescribe the strength of ground shaking, it still is the best available measure of intensity for use in loss estimates. More complex representations of ground shaking, for example, through a filtered "effective" peak motion, a single-degree-of-freedom linear response spectrum, a nonlinear spectrum, a time history of motion, and the duration of strong shaking, have the ability to be more accurate predictors of damage and loss. There is less agreement, however, on how to estimate these functions for a future earthquake, how to quantify the single- or multidimensional hazard associated with them, and how to derive an accurate predictor of damage from them.

However, use of MMI XI and XII should be avoided, or at least the meaning of these intensities should be carefully defined if used. The ground conditions for which prescribed intensities apply must be stated clearly, together with rules for taking into account below- or above-standard ground conditions.

Classification System for Buildings

The primary purpose of a classification system is to group buildings according to their seismic resistance for loss estimation purposes. Choice of a classification system depends on the availability of information relating ground motion to damage and on the funds available for compiling an inventory. Several standard classification systems have been developed, primarily for California construction, but in general it is necessary to tailor the system to suit local conditions.

Inventory

Inventory preparation is generally the most time-consuming and expensive aspect of a loss study. It is an exercise in locating and using available sources of information, carrying out some onsite inspection, and applying considerable judgment. The most difficult step is identifying the seismic resistance category for a building or group of buildings. Methods have been developed for abstracting an inventory from socioeconomic data in national data bases, but the panel believes that loss estimation efforts are better spent on field surveys and compilation of harder, more accurate construction class data.

It generally is not feasible to inventory all buildings individually, and attention is better focused on buildings that are seismically suspicious or are important to emergency response following an earthquake. Even when buildings are inventoried individually, they may subsequently be grouped regarding estimated losses, to help avoid legal and political problems that may result from singling out specific buildings as being hazardous. On the other hand, failure to disclose information about hazards may increase liability exposure, so the issue of specificity of an inventory should be handled with legal advice.

It is important to disaggregate the loss estimates to the smallest relevant political unit, except where this results in a small number of facilities that would compromise either the anonymity or statistical validity of the results.

Motion-Damage Relationships

The best information relating ground motion to damage are the statistics developed by the Insurance Services Office (ISO) from actual earthquake experiences. This information takes the form of average property loss ratios for selected classes of buildings versus intensity of ground shaking. The available data are best for single-family, wood-frame dwellings, and apply directly only to construction in California and some other western areas.

Because actual data of this type are so limited, and because for some purposes it is important to estimate the distribution of damage as well as the mean damage, damage probability matrices (DPMs) and fragility curves have been developed as alternatives to mean loss curves. Using a formalized procedure for obtaining and processing expert opinion, the Applied Technology Council (ATC) has published DPMs for a wide range of types of structures found in California. When the construction classes of ISO and ATC overlap, mean loss ratios deduced from the ATC DPMs are very similar to the curves of ISO.

The ambitiousness of the ATC-13 project has led to impressive accomplishments although the panel identified some criticisms of the method used to develop the ATC DPMs and of the manner in which they are portrayed. The final report of ATC-13 combines in one volume more data, a more complete methodological review, and more discussion by experts of the various tasks involved in the earthquake loss estimation process than any other single publication.

A major question is: How should motion-damage relationships be developed for use in loss estimates in areas other than California? The panel recommends that expert opinion be used to modify the California-based information for the types of buildings found in the area to be studied. Limited analysis of some selected archetype buildings can assist in this effort.

Evaluation of Losses

Combining the inventory with motion-damage relations leads directly to estimates for property losses, although it is necessary to be careful and explicit as to what value of buildings—replacement cost or market value—is used in the calculation. Usually, however, it is also necessary to estimate numbers of casualties. The data on which to predict deaths and injuries are very sparse, and considerable judgment is necessary in organizing available information to estimate casualties. The panel prefers a method set forth by ATC in which casualty rates are linked to degree of damage and class of construction; this is a rational approach but must be used with considerable judgment.

Estimates for the number of people requiring shelter are also important for planning of postdisaster operations, and for this purpose as well as for casualty prediction it is necessary to forecast the amount of severe damage rather than just the mean overall loss.

Any study should give a realistic assessment of the uncertainty in all loss estimates, such as by giving both best estimates and likely ranges.

Collateral Hazards

In addition to losses caused by shaking of buildings founded on stable ground, there may be losses caused by collateral hazards such as fault ruptures, landslides, liquefaction, tsunamis, and seiches. Losses from collateral hazards can be very important, in some cases dominating the overall loss. The key to evaluating these losses is in the identification of areas where such hazards will occur as a result of the scenario earthquake(s). Unfortunately, to do this systematically is a major and expensive task, and it may be necessary to rely on the judgment of experts. ATC has developed a rational sequence of steps for developing DPMs for structures affected by ground failure, once such areas have been identified by geologists and geotechnical engineers.

Lifelines and Emergency Facilities

In addition to buildings for residence and work, many other types of facilities are potentially important in loss estimates. Lifelines (e.g., railroads, highways and streets, water, electricity and sewage systems, and communication services) are vital to the functioning of a region and its emergency response capabilities following an earthquake.

Evaluation of lifelines involves the study of the possible failures of components (e.g., bridges or segments of pipelines) and the analysis of the effect of such individual failures on the overall performance of the system. The ATC-13 report has DPMs for various types of lifeline system components, which are the best available guidance, and the recent reports by the Building Seismic Safety Council (1987) are useful as well. For many lifelines, computer models for evaluating the effect on overall performance of the loss of some components will be available from utilities or agencies responsible for the lifelines, and the active cooperation of such utilities and agencies is the key to a satisfactory lifelines loss estimate. The final result is a scenario describing the ability of each lifeline to provide service following the earthquake.

Special attention must be given to those installations most essential for emergency response, such as fire stations and hospitals.

Susceptibility to structural damage must be assessed, but even if there is no structural damage a facility may be unable to function effectively if critical equipment has been dislodged or if important or dangerous contents have been damaged. It generally is necessary to visit each facility to assess structural resistance, and also to view the state of nonstructural conditions. ATC-13 contains organized expert opinion as to the time required to restore functionality of facilities, but the panel feels that these quantitative estimates contain more uncertainty than most other aspects of the overall process.

Even though each emergency facility is inventoried, legal and political difficulties generally require that a number of such facilities be grouped when stating expected losses. Thus, the result is a scenario describing the functionality of the emergency response systems as a whole, broken down by subareas, and not the state of individual facilities.

Facilities with a Potential for Large Loss

These facilities are not numerous and failure could cause enormous casualties as well as major property loss. Unless the loss and its likelihood can be stated with confidence as the result of detailed (and expensive) analysis, it should not be included in a large-scale loss estimate. However, the existence of such potentially hazardous facilities should be highlighted in the report.

Indirect Losses

It is not yet possible to make reliable quantitative estimates of the potential losses from fire following an earthquake, but a study should emphasize the functionality of the water supply system and the highway and street infrastructure as they relate to firefighting capability. It should also note high-risk areas or factors, such as time of year and weather. This has generally been done in the studies conducted by the National Oceanic and Atmospheric Administration and the U.S. Geological Survey. Precise quantitative loss estimates are not always necessary to point the way toward improvements in hazard reduction and emergency planning efforts.

An inventory of hazardous materials is desirable, but its preparation will depend on state and local inventories and existing programs of environmental health agencies and fire departments. There is no satisfactory method for evaluating the likelihood that storage systems will fail and cause release of these substances, and so this problem should be treated similarly to the topic of fires.

Evaluation of economic impacts other than damage is usually not part of a general-purpose loss estimate.

The Report

The report of a loss estimate study should meet two objectives. First and foremost, it should present results in a manner understandable to users in state and local government and to the public. Second, it should document the technical procedures used to compile the inventory and to calculate or otherwise evaluate losses, so that in the future the loss estimate can be updated. Careful design of the report is essential to achieve these two different and often conflicting objectives.

Independent Guidance and Review

Experts unaffiliated with the organizations conducting a loss study should provide independent guidance and review of an earthquake loss study. This policy is recommended for budgeting and implementation in future federally funded loss studies. The guidance and review might best proceed in steps—a review of the user-defined goals for the study, a review of the seismic hazard analysis, a review of the design for the inventory process, and so on. The final results of the study should also be reviewed.

This independent review is not suggested out of concern over the quality of past projects but to increase confidence in the results of future studies, to ensure better documentation of the methods used, and to conform to validation procedures generally accepted in the scientific and engineering disciplines.

User Needs

The foregoing guidelines respond to several of the identified user needs: involvement of local personnel, selection of the scenario earthquake(s), establishment of inventories with continued use for multiple purposes, disaggregation of inventory and losses to the smallest political unit consistent with the principle of averaging losses over an adequate number of facilities to ensure statistical validity and anonymity, and the reporting of the loss study results.

Several user recommendations conflict with the state of the art:

- Presenting a single number loss estimate rather than presenting a range of possible losses. Loss estimates are quite approximate, and it is considered essential that the uncertainty in any estimate be reported.
- Identification of specific, seismically suspicious buildings, structures, or facilities. In the absence of enabling legislation, identifying specific buildings as being likely to sustain damage could expose a loss estimator to legal suits or political repercussions. To be confident about the likely performance of a specific building involves a thorough study beyond the scope and budget of most loss estimates.
- Identification of expected releases of hazardous substances. In addition to the difficulties mentioned above, experiences during actual earthquakes are too limited to permit confident predictions.

At the outset of any study, the potential users and those performing the loss estimate must agree on compromises between what is desired and what is feasible.

Cost and Commitment Sharing

The panel is unable to provide guidelines as to the appropriate cost of a loss estimation study. It has been noted that a larger loss study budget can be justified on technical grounds because it leads to more accurate results. Another appropriate criterion for gauging how much should be spent on loss estimates is how extensively the information will be used. The political ramifications of cost sharing are also beyond the scope of the panel's review, but the related idea of commitment sharing should be considered in any debate over cost sharing.

While no one can promise that a loss study will lead to the passage of improved building or land-use ordinances, it is possible to schedule statewide conferences, as well as legislative briefings, for building officials and city planners following the completion of a loss study to consider its implications. State and local offices of emergency services can be expected to take a new loss study's findings into account in their earthquake disaster response planning, and this emergency plan revision effort can be scheduled to begin when the loss study is completed. Distribution of copies or summaries of the study and public information efforts can also be budgeted and planned prior to completion of a study. In the words of one observer and participant in the process of producing and implementing a loss estimate study, "Users should be required to commit themselves to the use of the information" (Buck, 1978).

RECOMMENDATIONS FOR RESEARCH AND DEVELOPMENT

Validation of Loss Estimation Methodologies

A strong need exists to demonstrate the validity of the components of the current loss estimation technology as well as the technology as a whole. Therefore, the panel makes two recommendations.

1. Following the next damaging earthquake to strike an urbanized area in the United States, after-the-fact "predictions" should be made using one or more predictive methods and results compared with the actual losses. The goals are to establish confidence in the use of the methods and to learn how the methods might be improved. The comparisons should be made for the methods as a whole—from magnitude and location to loss—and also for various components, such as losses estimated vis-à-vis a given intensity.
2. Opportunities should be seized for evaluating components of the overall methodology. Two examples from the inventory part of the problem are:
   - Where an exact inventory exists, such as with unreinforced masonry buildings in Los Angeles, compare these hard data with the inventories established by approximate methods;
   - Where an approximate loss estimation inventory has been prepared for a region, and this inventory can be disaggregated to small areas, prepare for comparison a complete inventory of one or more categories of buildings for a small area.

Corresponding opportunities will occur for other components of an overall methodology, for example, predicted and actual intensity of ground motion, or comparison of maps showing probable ground failure zones with maps locating actual failures prepared after an earthquake.

Sensitivity Analysis

For one or more methods, the panel recommends conducting sensitivity analyses to identify the significance of various possible errors on the overall loss estimate at each stage in the process. Such a study will give greater understanding of the uncertainty in loss estimates and will identify the parts of the overall process that contribute most essentially to this uncertainty. Such studies should be done using methods involving different degrees of approximation, and the resulting differences in the mean and ranges of estimated losses contrasted with the effort to prepare the estimate.

Development of Improved Methods

The ATC-13 report and other recent studies have made excellent contributions toward development of improved methods for evaluating losses. Continuation of this work will lead to improved methods with wide applicability. Thus, the panel recommends:

- A concerted effort should be made to develop a construction classification system applicable throughout the United States.
- Existing inventory methods should be compared to synthesize their strong points, rather than developing another new method. The NOAA-USGS method has featured the use of experienced earthquake engineers and locally knowledgeable real estate consultants or building officials to field sample a study area and relate the samples to land-use maps. The inventory method that would be most commonly used in the ATC-13 approach (Level 2), while not generally recommended by the panel, may be promising in combination with some field data to produce preliminary inventory outlines that would be used to design the detailed inventory process. The Gauchat and Schodek (1984) study of Boston housing, and the work by Jones et al. (1986) in Wichita, Kansas, incorporated aerial photography into the inventory process. While the panel does not recommend the use of aerial photography alone, it may be usefully combined with other data sources.
- The motion-damage-loss component of various methods should be compared to synthesize their strong points, rather than developing another new method. ATC-13 is innovative in its structured use of expert opinion and its development of relationships for new construction classes. The NOAA-USGS method has capitalized on historical loss data as well as judgment. The Central U.S.-Six Cities study (Allen and Hoshall et al., 1985) and the study of Boston housing earthquake vulnerability (Gauchat and Schodek, 1984) are notable for their explicit description of the archetype buildings that

represent each construction class, allowing experts to analyze thoroughly and debate the vulnerability of each class with the definition of the class held constant.

While work aimed at developing improved methods for estimating building losses should continue, special emphasis should be given to collateral hazards, such as ground failure and water effects, including the damage caused by such hazards, and to lifelines and emergency facilities.

As part of this effort, there should be a renewed attempt to develop a satisfactory quantitative scale for the damaging potential of ground motion. It is likely that using more than a single ground-motion parameter will be necessary. The panel accepts the use of MMI, but sees the possibility of developing an improved substitute.

Users' Needs and Study Uses

Research should be conducted to document exactly how previous loss studies have been used. For example, in what precise ways is a city's disaster response plan different because of the existence of a loss study? What public policy decisions were directly affected by a study?

In parallel with the development of improved loss estimate methods there should be improved utilization of study results. The problem is not just lack of information, but also lack of use of information.

Collection of Earthquake Loss Data

The process of collecting loss data immediately after significant earthquakes needs to be improved. For example, while reconnaissance efforts are common, collection of good-quality damage data and information on casualties, property loss, and functional loss requires noting the performance of all buildings of a given type in a given area. Documenting the performance of only the small number of buildings that experience dramatic damage does not provide the needed statistics.

As long ago as the 1923 Yokohama and Tokyo earthquake in Japan, or the 1933 Long Beach, California earthquake in this country, thorough field surveys of damage have been conducted. The techniques are readily available, but the administrative program to fund and publish this statistical type of data has often been lacking.

In addition, emphasis must be placed on collecting data for the occurrence and nonoccurrence of collateral hazards, the performance of lifelines, nonstructural components, and emergency facilities, and the containment or release of hazardous substances.

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Part II
Working Papers

Working Paper A
Types and Examples of Loss Estimation Studies

Potential users of loss estimates have different objectives, and a loss estimate study can only be called successful when it meets the purposes for which it is intended. Loss estimate studies can be categorized according to: type of losses estimated, kinds of facilities encompassed, certainty and detail, time span, and geographic scope.

These considerations can be combined in a variety of ways in a particular study, and it would be impossible to discuss all of them. The categorization scheme depicted in Figure A-1 is only one way of structuring this subject matter. Other ways of categorizing and analyzing earthquake loss estimation methods may be found in reviews of the field conducted from the 1930s to the present by Freeman (1932), McClure (1973), Boissonade and Shah (1982), Steinbrugge (1982, 1986), Reitherman (1985), Scawthorn (1986), and Whitman (1986). Table A-1 divides earthquake loss estimation methods into five basic types, which can be characterized in terms of the combination of aspects presented in Figure A-1.

- Type I: General
- Type II: Hazard Reduction
- Type III: Emergency Planning
- Type IV: Financial Risk
- Type V: Economic Impact

The methods presented in Figure A-1 all have a low degree of

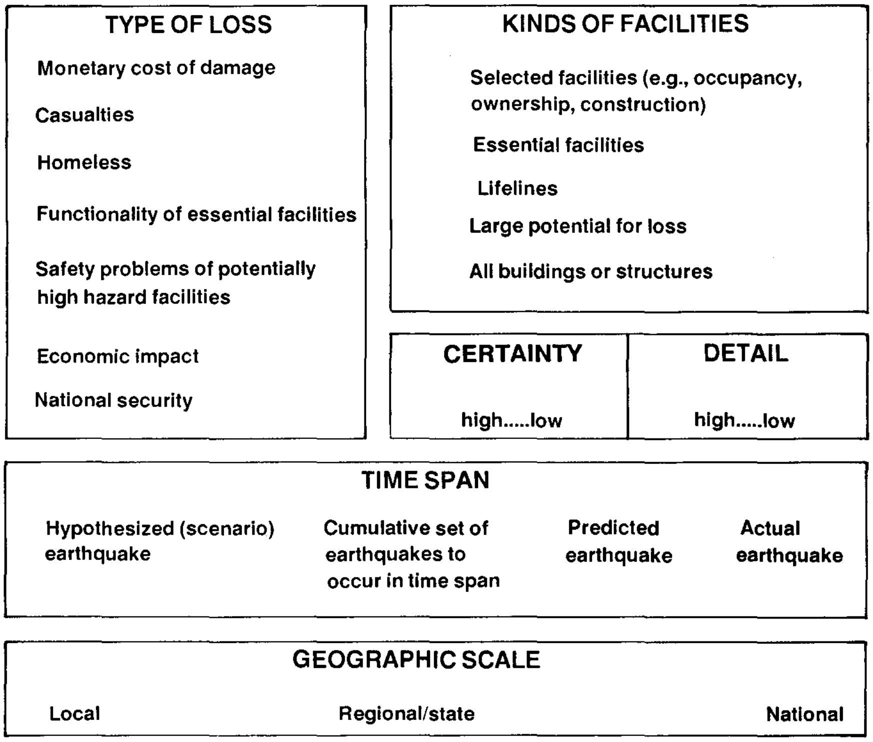

FIGURE A-1 Aspects of earthquake loss estimation studies.

certainty, which reflects the inherent uncertainty in the field of earthquake loss estimation and is not necessarily indicative of methodological errors or weaknesses in any particular method. In many engineering applications, the term *accurate* connotes a method that can reliably produce estimates that do not deviate much, say no more than perhaps 10 percent, from the actual results. Earthquake loss estimation methods that are reliably of such accuracy (even in the case of facility-specific studies with high levels of effort) do not exist. Earthquake loss estimates that might prove to be in error by a factor of 3* are often considered accurate in this field. The word *certainty* is used here to describe the degree of confidence in a loss estimate; an estimate with low certainty will have a large range of uncertainty

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*See footnote 2 in Chapter 4.

TABLE A-1 Purposes, Users, and Examples of Types of Loss Estimation Studies

Type of Study	Purpose	Users	Examples
I: General	Identify the general scope of the earthquake problem to establish a basis for planning, prioritizing, and funding earthquake risk reduction efforts	General public as well as all other users listed below	J. H. Wiggins Company and Engineering Geologists, Inc.1979; Algermissen et al., 1972
II: Hazard reduction	Guide hazard reduction actions to reduce physical damage	Legislative, regulatory bodies; government officials and staffs; utilities and corporations	Alfors et al., 1973; Ward, 1986; Office of State Architect, 1982; Los Angeles City Planning Department, 1980
III: Emergency planning	Facilitate more efficient emergency response	Emergency response agencies; utilities and corporations	Algermissen et al., 1972; Davis et al., 1982a,b
IV: Financial	Rate earthquake risks of individual properties or collective risk of portfolios	Insurance, mortgage lending, and investment industries	Freeman, 1932; California Department of Insurance, 1985; Working Group Earthquake Hazard Reduction, 1978
V: Economic impact	Estimate economic losses (including indirect, long-term economic impacts)	National security agencies and national or regional planners	Applied Technology Council, 1985

about the best estimate, and conversely one with high certainty will have a small range of uncertainty.

Specific examples of loss studies follow.

TYPE I: GENERAL

An example of this broadest type of loss study is the research funded by the National Science Foundation (NSF) that produced property loss estimates for earthquakes as well as floods, expansive soil, landslides, hurricanes, and tornadoes (J. H. Wiggins Company and Engineering Geology Consultants, Inc., 1979) for cumulative property losses during the years 1970 to 2000. Life loss was also estimated to some degree as well as the reduction in losses that could be expected by application of hazard reduction actions.

The scope of such a study is very broad both geographically and in terms of considering more than one hazard. Although the results are more aggregated and less certain than those from studies focusing on an individual region and only one hazard, such comprehensive estimates are needed. Comparisons among hazards, between the continuation of policies or the initiation of certain preventive actions and between the losses that would likely occur in the near term versus the long term, can be useful decision-making tools, especially at the national policymaking level. This type of study also enables comparisons between the relative degree of risk faced by different states in relation to fixed analytical benchmarks, in contrast to comparisons of losses resulting from scenario events that vary in likelihood from one study to another.

General studies are necessary if the intended application, such as selecting among policy options and evaluating the effectiveness of loss reduction programs, requires statements that say, for example: "Unless significant new steps are taken, the costs of replacing or repairing buildings destroyed and damaged by the nine natural hazards studied, during a typical year, are likely to increase more than 85 percent in the 30-year period between 1970 and 2000" (J. H. Wiggins Company and Engineering Geologists, Inc., 1979).

Figure A-2 illustrates the characteristics combined in Type I national-scale loss estimation study using the above-mentioned study as the example. The types of losses estimated by such a study may vary, but two basic components are direct monetary cost of damage and casualties. The time variable is defined in terms of the cumulative losses estimated to occur in a given time span, in this case 1970-2000. The scope in terms of the kinds of facilities extends to all buildings, and both certainty and detail are relatively low. This study could also qualify as a Type II (hazard reduction) study, which illustrates the overlap between categories.

Regional Type I studies have fulfilled a variety of purposes, perhaps their most frequent use being as an emergency planning resource. The first of the studies (Algermissen et al., 1972) sponsored

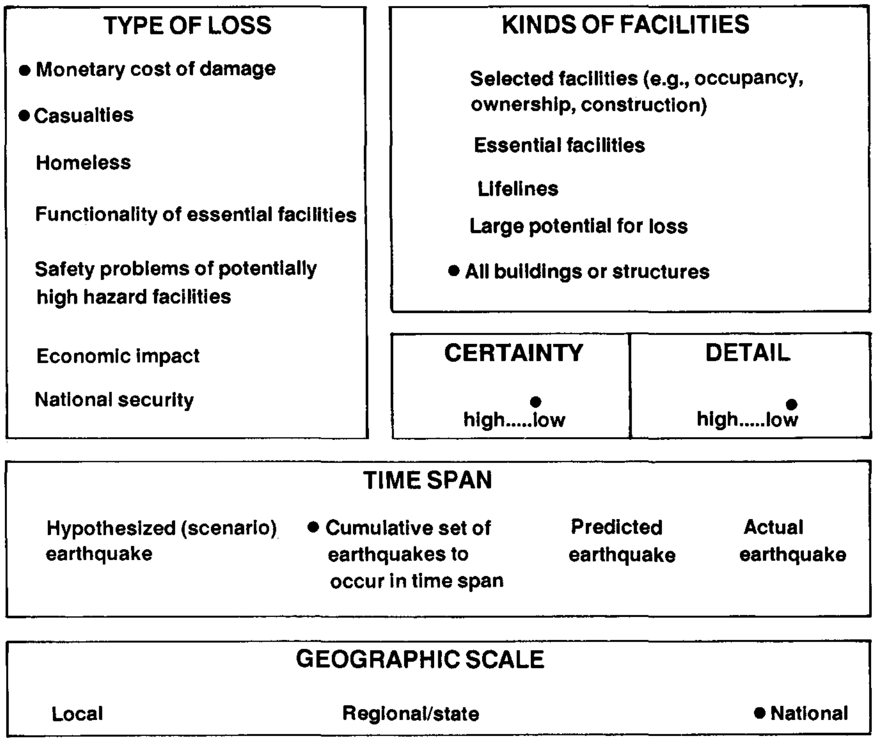

FIGURE A-2 Aspects of a Type I, national-scale loss estimation study, using the example of J. H. Wiggins and Engineering Geology Consultants, Inc. (1979). Key: ● = aspects that pertain to this type of study.

by the National Oceanic and Atmospheric Administration (NOAA) is a typical example of a Type I regional-scale study.

This study of the San Francisco area projects a broad range of losses. Later NOAA and U.S. Geological Survey (USGS) studies are quite similar in their broad scope. (In the mid-1970s, earthquake loss estimation projects and staff were shifted from NOAA to USGS with no significant change in the type of studies undertaken nor the methods used.) Casualties were estimated by time of day, by county, and according to hazard sources, that is, casualties that would occur within hospitals, schools, or dwellings are differentiated from other injuries and fatalities. Outages of utility services, transportation routes, and other types of functional losses suffered by lifelines were estimated. Property losses involved only single-family dwellings. An updating loss study (Steinbrugge et al., 1981) also estimated property losses for commercial and most other building types. Figure A-3 shows the table of contents from the first NOAA study in order to indicate its scope, which is similar to later NOAA-USGS studies.

Type I studies are often the first type of study to be conducted in a region. They are essential tools of seismic safety advocacy. As public policy, earthquake hazard reduction, or emergency planning activities develop, other studies with narrower foci may be conducted to support more specialized risk reduction efforts. Type I study elements are often adapted for use in other kinds of studies, and in some cases a Type I study can serve some of the more specific purposes requiring Type II, III, IV, or V studies (Figure A-2).

The regional-scale study is much finer in detail than a national study, but at the cost of a smaller geographic scope. This trade-off between covering a larger area at a shallower level versus a smaller area in-depth is an inescapable constraint on all earthquake loss estimation studies. Figure A-4 categorizes a Type I regional study as including all but the overall economic impact and national security types of losses; it may include the entire range of kinds of facilities. Its loss statements have usually been predicated upon scenario events, and the certainty and especially its detail are greater than in the case of national-scale studies. In most cases, it is important that the study area boundaries or subarea boundaries match political boundaries demarcating cities or counties.

TYPE II: HAZARD REDUCTION

Type II studies primarily support hazard reduction efforts, and the primary user is government agencies which adopt building codes regulating new construction or retroactive ordinances pertaining to existing hazardous facilities, land-use plans, and other laws and policies. Type I studies are often used for this purpose, but Type II studies emphasize this hazard reduction purpose with more specific reference to the codes, ordinances, voluntary standards, or other concrete policy options under consideration, and limit their scope to the specific physical hazards, resources, or jurisdictions of interest.

On a state scale, cumulative losses over future time spans have been estimated in studies of California (Alfors et al., 1973) and Utah (Ward, 1986). These two studies fit the pattern shown in Figure A-5, with the scope of the California study extending to all buildings and the Utah study focusing on particular types of facilities, such as schools and hospitals. By using a multidecade time

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FIGURE A-3 Table of contents of the first of the joint National Oceanic and Atmospheric Administration and U.S. Geological Survey studies. Source: Algermissen et al. (1972).

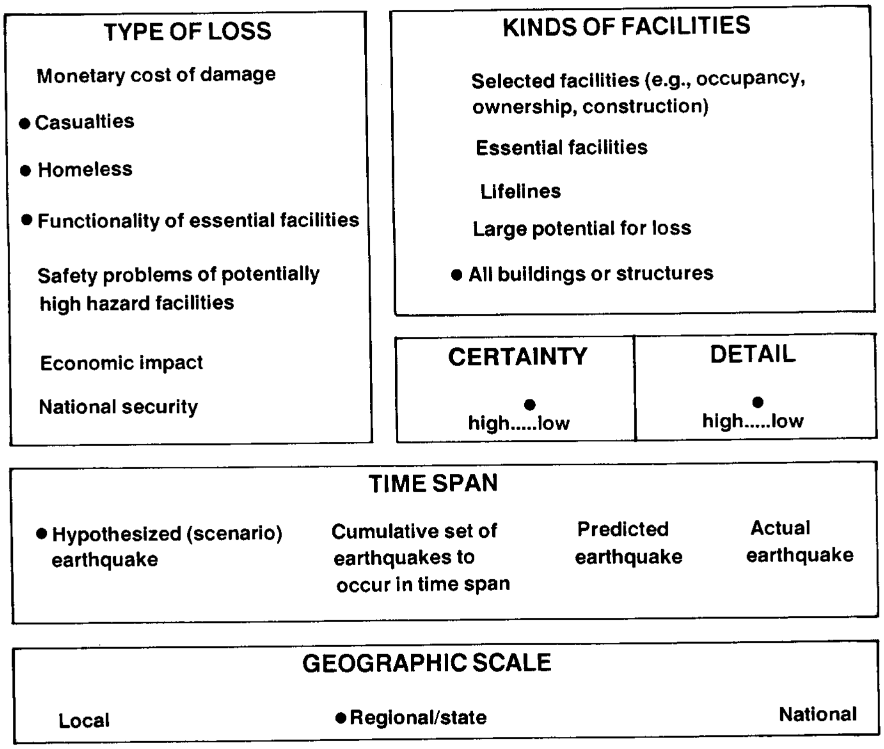


FIGURE A-4 Aspects of a Type I, regional-scale loss estimation study, using the example of Algermissen et al. (1972). Key: ● = aspects that pertain to this type of study.

span and estimating cumulative losses, these studies provide a way for policymakers to develop long-term risk reduction strategies.

The study of 229 hospitals having 1,077 buildings in six southern California counties (Office of State Architect, 1982) is a Type II study of a large urban region within one state, with the scope limited to one kind of occupancy. Vulnerabilities were rated without regard to scenario or cumulative losses. On a broader geographic scale, limited also to one kind of facility, a survey of 800 major buildings on University of California campuses was conducted (McClure, 1984). Losses in this case were estimated in terms of the relative risks faced by building occupants, assuming the buildings were subjected to the same strong level of shaking. These last two examples of studies indicate that for some hazard reduction purposes, relative

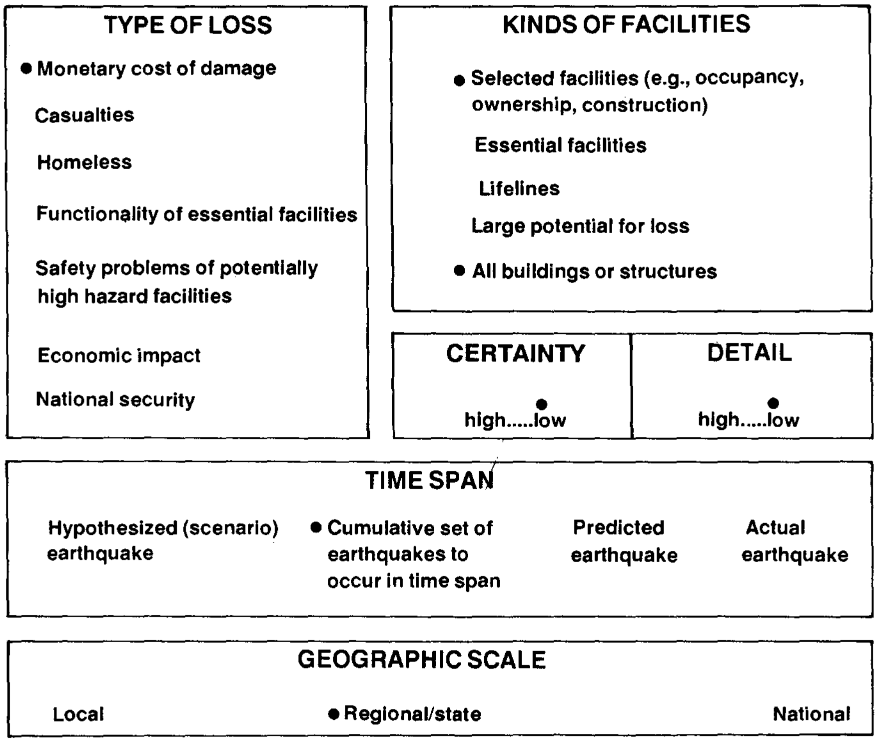


FIGURE A-5 Aspects of a Type II, state-scale loss estimation study, using the examples of Alfors et al. (1973) and Ward (1986). Key: ● = aspects that pertain to this type of study.

risk ratings rather than estimated numbers of casualties in a given scenario earthquake may be the appropriate goal of the analysis.

An example of a local-scale hazard reduction study is the environmental impact report accompanying an ordinance that went into effect in Los Angeles in 1981 requiring the hazards of about 8,000 unreinforced masonry buildings to be reduced (Los Angeles City Planning Department, 1980). In this study, only one kind of structure was studied, only life losses were of concern, the time span was in terms of a future scenario earthquake, and the certainty and detail were higher than with typical Type I studies (Figure A-6).

This loss estimate study was calibrated with the earlier NOAA study of losses estimated for a broader area and without an explicit breakdown of casualties related to classes of construction (Algermissen et al., 1973). The 1980 Los Angeles study provided the conclusion

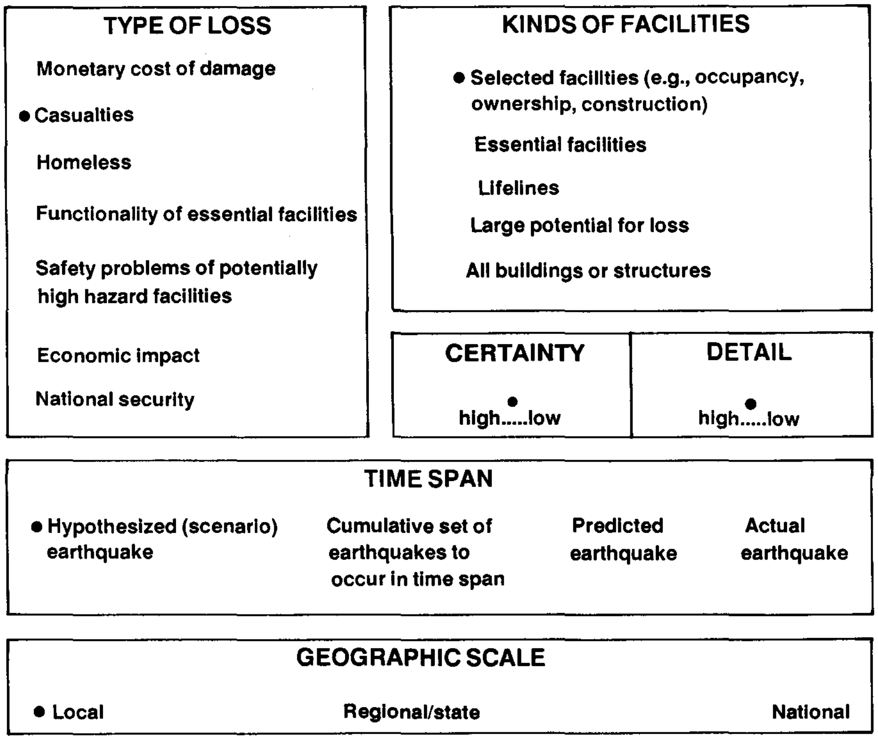


FIGURE A-6 **Aspects of a Type II, local-scale loss estimation study, using the example of Los Angeles City Planning Department (1980). Key: ● = aspects that pertain to this type of study.**

that in a great earthquake (the same scenario earthquake used in the 1973 NOAA study), the number of fatalities within the city would decline from 8,500 to 1,500 if the retroactive standards for unreinforced brick buildings were implemented.

TYPE III: EMERGENCY PLANNING

The NOAA-USGS study (Type I) also fits this category, but another example is the work done by the California Division of Mines and Geology to identify functional losses to lifelines in the urban areas of Los Angeles (California Division of Mines and Geology, in progress; Davis et al., 1982a) San Francisco (Davis et al., 1982b; Steinbrugge et al., in progress), and San Diego (Reichle et al., in progress). The characteristics of this type of study, at the regional scale, are shown

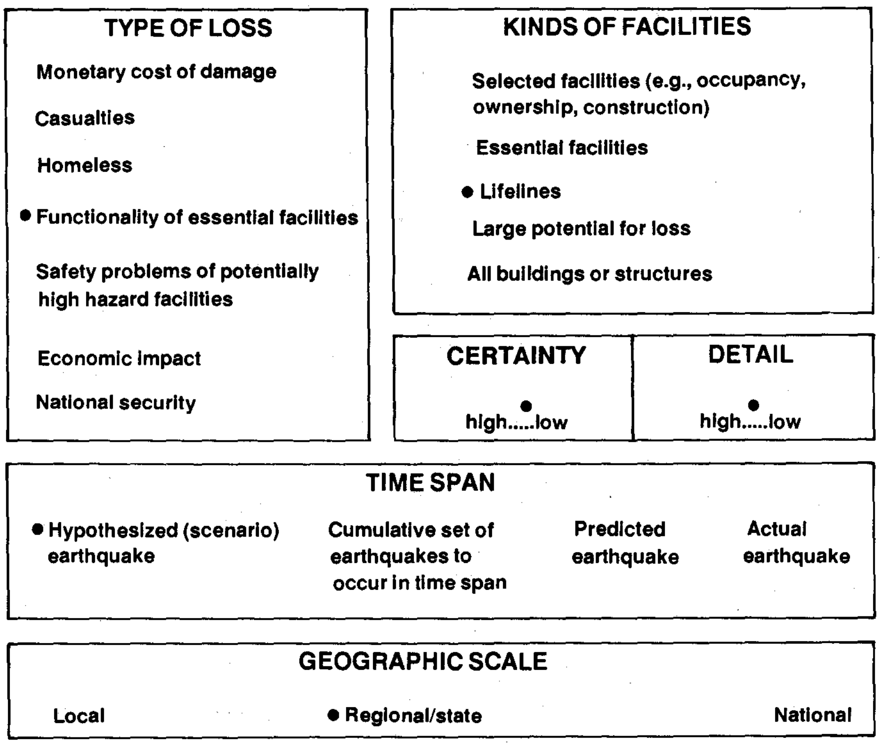


FIGURE A-7 Aspects of a Type III, regional-scale loss estimation study, using the examples of Davis et al. (1982 a,b). Key: ● = aspects that pertain to this type of study.

in Figure A-7. When such a study is devoted to a smaller geographic area, the detail of the results increases, as shown by the finer scale of the maps used to portray the results. The fire department of Orange County, California has extended the detail of one type of emergency planning study concerning transportation routes to the level of the neighborhood surrounding each fire station, looking at each roadway route that leads from the station to the outside area and considering potential route blockages such as collapsing bridges or building debris (C. Nicola, Orange County, California, Fire Department, personal communication, 1986). This might be called the "street map" scale of Type III studies.

TYPE IV: FINANCIAL RISK

This type of study is distinguished by its focus on direct property loss and the fact that its primary user for many decades has been the insurance industry, and to a lesser extent the mortgage lending and investment industries. Several examples are provided in an earlier, widely published work in the field of earthquake loss estimation, *Earthquake Damage and Earthquake Insurance* (Freeman, 1932). Freeman produced regional-scale property loss estimates for all areas of the United States; the nature of this study is diagrammed in Figure A-8. Another study that fits this pattern of a state- or regional-scale financial study is the annually updated report issued by the Department of Insurance in California, which estimates aggregate losses in each of the various regional-scale zones of the state for properties covered by earthquake insurance (California Department of Insurance, 1985).

In these two cases, the rating of the risk of experiencing property damage or insurance losses extends essentially to all buildings, and the intended user is broadly defined as the property insurance industry or government regulators having industry-wide insurance concerns. Some Type IV studies conducted for a given company, however, limit themselves to a smaller scope—those facilities that are contained in that particular company's portfolio of insured, financed, or owned properties.

An appendix to a comprehensive report by the Office of Science and Technology Policy (OSTP) discussed one particular aspect of the subject matter that falls under the heading of Type IV studies: the risk faced by various sectors of the financial industry during certain possible earthquake prediction situations (Working Group on Earthquake Hazards Reduction, 1978). This analysis pointed out the need to divide a financial sector, such as mortgage lending, into smaller categories when analyzing earthquake risk, because of the different characteristics in terms of assets, liabilities, income, and expenses of institutions such as commercial banks, savings and loans establishments, and life insurance companies. This type of study is an exception to the rule that financial risk studies generally focus on the monetary cost of damage as the type of loss of concern.

TYPE V: ECONOMIC IMPACT

Type V studies deal with the decrease in the economy's production of goods and services that might result months after the

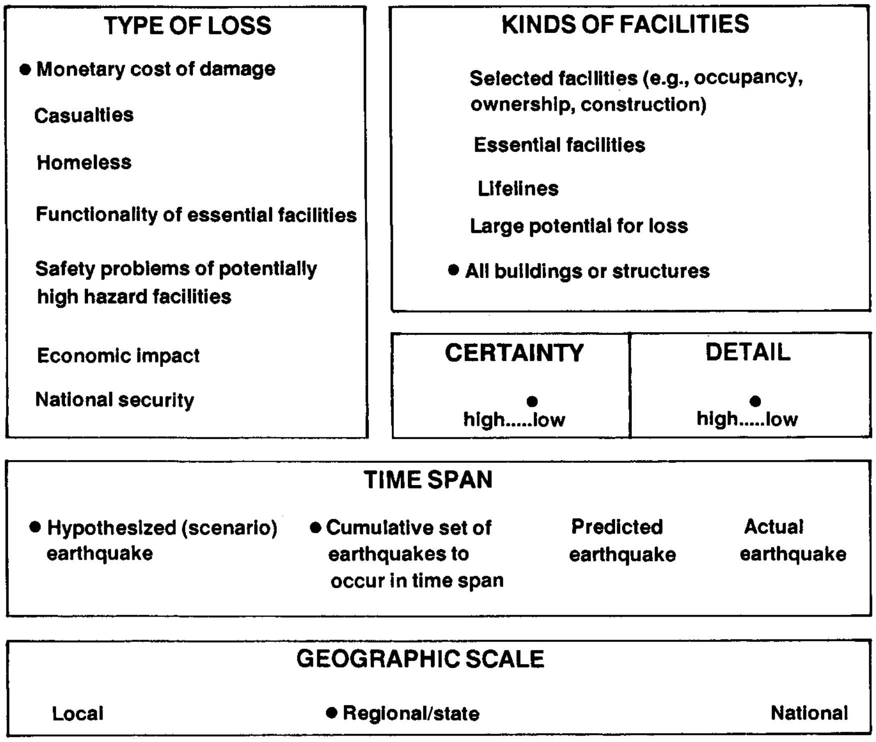


FIGURE A-8 Aspects of a Type IV, regional-scale loss estimation study, using the example of Freeman (1932). Key: ● = aspects that pertain to this type of study.

earthquake, rather than just the immediate damage. The most recent effort of this type has been initiated by the Federal Emergency Management Agency (FEMA). The ATC-13 study is the engineering component of the overall FEMA method that will use the ATC-13 estimates of initial damage and decrease in functionality to forecast the effects on local, regional, and national economies and national security. Therefore, the ATC-13 method may also be thought of as a Type I, general-purpose loss estimation technique. The primary motivation for the ATC-13 study was concern over the ability of defense industries to supply militarily essential products after a major California earthquake, and it was requested by the National Security Council (NSC). Figure A-9 illustrates the basic characteristics of this proposed type of study (which has to date been implemented only in pilot projects). The ATC-13 or earthquake engineering portion of

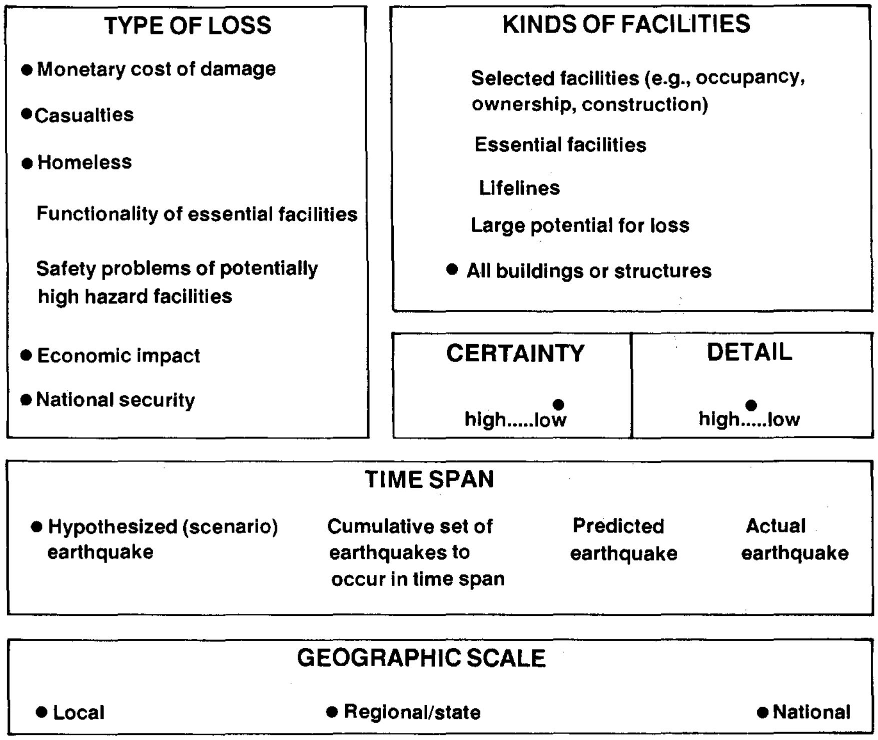


FIGURE A-9 Aspects of a Type V, regional-scale loss estimation study, using the example of FEMA Fedloss Method and its ATC-13 engineering component (Applied Technology Council, 1985). Key: ● = aspects that pertain to this type of study.

this overall economic loss modeling method could also be applied to other purposes and diagrammed differently, but is outlined here in the context of its original purpose. ATC-13 as of this date has not been used to produce a complete, published loss study.

Much detail exists with the FEMA/ATC-13 type of study because its aim was to develop an inventory of almost every facility according to about 500 economic sectors for most of the state of California. It makes precise statements about the amount of damage and the functional loss that could be suffered in each facility. It includes industrial tanks, tunnels, and other nonbuilding structures in greater detail than other methods. The ATC-13 method develops losses on the scale of each individual factory, for example, first estimating damage and then determining the number of days after the earthquake before 30 percent, 60 percent, and 100 percent of pre-earthquake functioning is restored.

Because hard data or relatively accurate field-acquired information describing the construction characteristics of all buildings in a region do not exist, and because of few data on the connection between building damage and loss of function, the ATC-13 method provides inferences for constructing an inventory from readily available socioeconomic data bases. Expert opinion was used to develop damage and loss relationships for a large number of types of facilities.

The ATC-13 example is a reminder that when great detail is sought on a large scale—requiring that the loss estimation method answer a number of difficult questions in a detailed, quantitative way—certainty must be sacrificed. Widely accepted, easily applied, and objective ways of rating the certainty of loss estimate methods do not exist, and the issue of what constitutes acceptable certainty or acceptable detail can be decided only by reference to the fitness of the study for its intended purpose. This again brings up the important subject of the users and uses of loss estimation studies, a theme throughout this report.

Working Paper B
User Needs

IDENTIFICATION OF THE USER COMMUNITY

Early in the panel's deliberations it became clear that one of the most important considerations in examining the different methods of estimating earthquake losses would be the users' needs. This required defining who the users were so that their particular needs could be reflected in the panel's assessment of different loss estimation methods.

Many different groups and sectors potentially could have been included as users. A subpanel developed several sampling strategies, as well as research designs for a comprehensive study of user groups. For example, the panel could have considered the needs of such diverse elements as federal, state, and local administrators and officials, insurance companies, bonding companies, social scientists, the engineering and scientific communities, public information institutes, and other groups. Indeed, the different user groups in each of these sectors pose very complicated sampling and design problems. After considerable discussion with FEMA and USGS representatives, the user group was defined to include only state, county, and local public officials.

Several factors led to this simple definition of users:

- The scale of a study that would include all potential groups would be large.

- The time frame of the panel was relatively short, prohibiting a large-scale study.
- Funding for such a large-scale study was not possible within the panel's budgetary constraints.
- The funding agency's major clientele were public sector entities invested with protecting the public health, safety, and welfare.

Given this user group the panel's goal was to determine needs and to evaluate different methods in terms of meeting the users' requirements. It was believed that the better such studies met the requirements and needs of the user community the more likely the studies would be utilized in planning for, responding to, mitigating the effects of, and recovering from a major damaging earthquake. Even with this limited definition of the user community, the selection of state and local officials for inclusion in the study presented some significant problems that limit the extent to which the subpanel's recommendations may be generalized and that warrant discussion.

Options for obtaining the views of users included a questionnaire survey based on a scientific national sample, a similar survey with a smaller sample, in-depth discussions with some very experienced users, and a workshop. The workshop option was selected primarily on the basis of time and budget. The results of opinions solicited in the workshop, presented later in this paper, should not be construed to be statistically valid as a representation of state and local users.

The Method for Selecting Users

The first step was to obtain a list of users that could be used in constructing an appropriate sample. After extensive consultation with USGS, FEMA, and the COSMOS Corporation, consultant to the panel, a user was defined to be an appointed or elected public official who could be involved in developing data for use in loss estimation studies or in making decisions, based on those studies, which resulted in a lowered risk to the community. This definition, although limited, included officials in such functional positions as mayors, city managers, planners, directors of public works departments, building code officials, county commissioners and managers, and emergency service personnel at the local and state level. The geographic scope of the list was limited to approximately a dozen higher seismic risk areas of the United States (Table B-1).

The panel could not develop what it considered an adequate list.

TABLE B-1 Participants in the Workshop, by Area and Level of Government

Area	Level of Government City	 County/Regional	 State
California	3 emergency services officials 2 building code officers 1 city manager 1 planner	1 regional earthquake program manager	1 state earthquake program manager
Central United States		1 county commisioner	1 state emergency services official
Northeast	3 emergency services officals		1 state emergency services official
Puget Sound, Washington	1 city council member 1 emergency services official		
Utah	1 mayor	1 county residential supervisor	2 state emergency services officials
Alaska	1 planner		1 state emergency services official
Hawaii			1 state emergency services official
South Carolina			1 state emergency services official
Puerto Rico			1 state emergency services official
Total	14	3	9

Eventually the list of local government users included some planners, building code officials, and a few council members, mayors, and managers (Table B-1). The state list of users was overrepresented by emergency service managers. Finally, the list was overly representative of California users, which is not surprising given the fact that over a dozen loss studies have been conducted there.

The workshop invitees were selected from lists of potential users supplied by federal agencies, and very few actual users are present in this pool at this time; there was a limited representation of the functional positions at the state and local levels, and geographic affiliations were not nationally representative. All of these factors make it necessary to address briefly the limitations of the data collected.

Data Sources and Limitations

The panel has relied on the results of the survey, the small group discussions, and the presentations by technical and user community members to suggest the users' needs. This information has been utilized to broaden the perspective of the panel in its deliberations. The workshop provided the key instruments for gathering data, and a few factors require discussion. The panel fully recognizes the limitations of these data sources and the fact that generalizing solely on the basis of the workshop cannot be done with much certainty.

The major goal of the workshop held September 22, 1986 was not to train or even educate the participants in loss estimation studies. Rather, participants were invited to educate members of the panel about the requirements and needs of the community which would or potentially could utilize loss studies once they were completed. The workshop was designed to provide several different approaches and methods by which panel members could determine user needs.

The survey instrument administered to participants was designed to gain insight into participants' needs and familiarity with loss studies. The instrument was administered twice during the workshop, but not to determine the effectiveness of the workshop. The panel was far more interested in the responses to the first questionnaire prior to participant exposure to the speakers, because of the focus on determining what state and local users (or potential users) of loss studies believed they needed to utilize such studies. Hence, the findings below focus almost entirely on the users' responses to the first questionnaire.

Finally, small group discussions addressed four questions, three of which were common to all groups. The questions reflected issues briefly covered in the questionnaire but requiring additional attention.

These data sources are utilized in this working paper and are suggestive and informative. The panel makes no claim that the findings can be generalized to the larger user community.

FINDINGS

The discussion in this section is based on findings about user needs from the three data sources discussed earlier.

Usefulness of Prior Loss Studies

A major concern of the panel and the federal agencies focused on the widespread belief that previous loss studies were not being adequately utilized by the user community. Many of the panel members who had been involved in some of these loss studies indicated their disappointment over the lack of use. As a result, workshop participants were asked about their exposure to such studies and the usefulness to their agencies and units of government.

Twelve of the 26 workshop participants indicated either that they had never seen the results of a loss study or that the study in which they had participated was not yet completed. The remaining 14 participants were asked how useful the results of the studies were for a variety of activities: mitigation efforts, planning and preparedness efforts, response and recovery planning, land-use planning, building code design, and efforts to educate the public and elected officials. Participants did not indicate that the results were very useful for any one activity, but a majority of participants found these studies useful (either very or somewhat useful) for the spectrum of activities. The most important use of these studies, according to small group discussions and questionnaire results, was their use in educating elected officials and the public about the seriousness of seismic threat and the need to take action.

There was clear agreement that such studies have been and should be used to advocate the importance of seismic programs in order to obtain greater emphasis on actions that reduce the effects of an earthquake. Additional uses that received strong support among participants were public awareness and education programs and emergency response planning.

General Barriers to Utilization

Participants were asked why they believed loss studies were not utilized in developing public policy. Most important, and a general theme in the utilization issue, was the lack of involvement by state and local officials and policymakers in the entire study process. Participants indicated that too often the "experts" conducting the loss studies proceeded without regard to whether the users would understand what the results addressed or meant. In addition, some users indicated that the conflicts and disagreements among professional and technical experts had seriously undermined any efforts to utilize such studies. Workshop participants also stated that some reports were completed in an untimely fashion and, when delivered, were written too technically.

All of these factors seem to contribute to the final barrier to using these studies—the lack of support among elected officials for taking action and making policy. If the above-identified barriers were removed it would not ensure greater support from policymakers, but it would help. If these loss studies are to be used, in part by advocates of seismic planning and policy, then officials must be involved in the loss estimation study process and the reports must be understandable, less technically presented, and timely.

Defining the Seismic Hazard: The Earthquake Scenario

An issue that has emerged in many loss studies emphasizes how helpful it is to policymakers and planners to have a loss study based on the most damaging historical earthquake. Participants in the workshop strongly indicated their desire to have studies focus on major but likely earthquakes. In addition, participants (about two-thirds) believed it was either very or somewhat important to have different estimates of loss for different seasons of the year. Finally, all of the participants believed it important that losses be estimated for earthquakes occurring at different times of the day. In short, if the users' needs are to be met, loss studies should include these features: most likely earthquake to cause significant damage, seasonal estimates of loss, and estimates for the event occurring at different times of the day.

Geographic Focus of Study

Users at the state, region, county, and local level have different needs and requirements. In addition, recent research indicates that the key actors' functional positions influence their support for seismic planning and policy (Mushkatel and Nigg, 1987). Nowhere are these different needs more manifest than in the data addressing the geographic focus of the studies. The small group discussions strongly indicated that the level of government one is employed by influences the desired geographic focus. Hence state participants wanted the loss studies to be for either states or regions, whereas local government officials desired a local focus.

Local government participants used several examples of studies that were of such large geographic focus that they were of little value to localities, particularly when the loss estimates and data could not be disaggregated to the local level. In addition, for individuals in some functional positions the most valuable data and loss estimates would be site specific, which may be impossible or at a minimum very costly.

Workshop participants also discussed some elements of the inventory data used in loss studies. There was agreement that a multitude of data from both public and private sources should be utilized in such studies. Yet there was also the belief that too frequently the data utilized were not maintained or accessible to the users and that in new studies firms or governmental entities had to recollect or rediscover much of the same data. Thus the users urged those doing loss studies to take steps to standardize the process for collection, maintenance, and dissemination of inventory data.

Types of Information in Loss Studies

Loss studies have produced much information about projected losses for different types of structures serving various purposes. Participants at the workshop were asked to rank the importance of loss estimates to 19 different structures and facilities along a four-point ordinal scale from very important to not at all important. Over 90 percent of the participants indicated that estimates regarding emergency public facilities (96 percent) and hospitals (92 percent) were very important. Almost as vital were loss estimates for water distribution systems (88 percent), electric power systems (80 percent), hazardous materials storage sites (80 percent), and highway systems (76 percent). The least important information concerning losses according to workshop participants were port facilities (14 percent) and government buildings (32 percent).

These rankings are relative, and tests of statistical significance are inappropriate given the data base and sample. They suggest, however, that the participants seemed to focus on the response and preparedness components of the disaster and the ability of authorities to estimate losses to facilities critical for emergency response. This focus may be a function of the makeup of the participants (functional position) or of the fact that most loss estimate utilization has been identified somewhat with emergency response and preparedness.

Specificity, Accuracy, and Credibility of Loss Estimates

An issue discussed at length by the panel is the importance of accuracy in loss estimates and the trade-offs between accuracy (certainty) and specificity. To the user community an important point is the credibility of the estimates. A consistent theme was that the earthquake scenario and the estimates of losses had to be generated from a recognized and credible source and, most important, be plausible. Small group discussions indicated that some estimates were based on extreme events with such high loss estimates that they had not been taken seriously. In some instances, public actors viewing the expected losses were so overwhelmed they felt local and state action would not be feasible or would not make any difference because the problems were intractable in light of the estimates.

Given the amount of error loss studies potentially contain, steps must be taken to ensure the greatest amount of credibility to loss studies. The greater involvement of state and local authorities throughout the loss estimate study process will increase the likelihood such estimates are taken seriously.

Ideally, these loss estimates could be both certain (estimation of total losses) and specific or detailed (losses to specific locations or sites). When participants were asked to select between specificity and certainty, a majority chose specificity (60 percent) as the more important to them for utilizing the information. This is especially important for hazard reduction programs. This desire for specificity is not surprising but may cause some difficulty because of the state of the art in loss estimates. Even more disturbing was the fact that of those state and local users at the workshop who had some familiarity with loss estimates, only 17 percent were very confident of the loss predictions. Obviously this lack of confidence contributes negatively to the credibility issue discussed above. One frequently mentioned problem was that the ranges of predicted losses in life and property were too great to be very useful for planning purposes.

Finally, participants were asked on the survey to indicate how reliable different loss estimates must be for utilization. The results are difficult to interpret since state and local users might be willing to forego some information reliability if the type of structure or its purpose is sufficiently important. Keeping this potential tradeoff in mind, participants indicated that it was most important to have very reliable information for dams (48 percent), electric power systems (44 percent), natural gas and water distribution systems (40 percent), and highway systems (36 percent). Participants indicated it was least important to have very reliable information about airports

(4 percent), radio and television facilities (8 percent), government buildings (12 percent), and residential structures (16 percent).

Obviously state and local officials want as much specific and credible information as possible. Yet these requirements, as reasonable as they seem, involve real costs. It is in this light that the information collected on users' willingness to spend takes on additional significance.

Cost, Willingness, and Ability to Spend

The issue of the willingness and ability to spend scarce fiscal resources on loss studies by the state and local user community has several important dimensions. First, the proposed sharing of costs between FEMA and state and local governments for other programs may in the near future include the monies used to finance loss studies. Hence, the panel determined it would be appropriate to investigate not only the needs of users, but also their willingness and ability to spend monies to obtain loss estimates. Furthermore, it is often thought that if a government spends some of its own resources for a study it is more likely to use the results.

One of the questions included in the survey requested workshop participants to indicate what amount their office or agency would be willing to spend for an earthquake loss study. The most frequent response category selected was less than $75,000. Because of the way the question was worded it is impossible to determine how many of the 71 percent who indicated they would spend $75,000 or less would spend nothing for such a study. Almost 20 percent of the participants did not answer the question at all, and only 10 percent indicated they would spend $225,000 or more.

In short, state and local users perceive a lack of willingness or ability for their agencies and offices to expend monies for such studies. In addition, more than 80 percent of the state and local users indicated that their current budgets did not contain adequate funds for such a study. Questions about future budgets were not asked.

Finally, despite this apparent inability or unwillingness to fund loss studies, users expressed support for sharing costs. When asked what percentage their governmental units should be responsible for, 59 percent of the participants indicated between 41 and 50 percent, 16 percent signified less than 10 percent, and 11 percent noted more than 50 percent.

Workshop data reveal support among state and local users for cost sharing, but they also show that current budgets are not sufficient to assume these costs. The last constraint on willingness to spend involves the total cost of the studies. Workshop participants (71 percent) indicated they would only spend less than $75,000 for a loss study. Hence, there seems to be a strong desire to hold down costs because current budgets are inadequate to finance the studies.

The Loss Study Report and Its Dissemination

One explanation for the lack of willingness and/or ability to spend is the users' lack of satisfaction with such studies. The survey data cannot test this explanation, but a consistent viewpoint that emerged at the workshop was that current loss studies are understood only with great difficulty by the user community. A major problem is the results are not presented in a way that makes clear their implications for seismic planning and policy development.

Users at the workshop also criticized the presentation of the results, most often citing them as being too technical. They supported the presentation of technical materials in an appendix, rather than in the body of the report. In addition, the problem associated with inventory and other data bases reemerged. Users want the data to be accessible to them after the report is finished. Such accessibility would permit disaggregation to lower units of government or to a smaller geographic area.

The participants often shared the perception that once such studies had been completed they were not disseminated adequately. Too little attention was paid to disseminating the findings to the potentially large community of users. Participants believed that more attention should be given to dissemination in the loss study process, and suggested that either state or local government agencies be responsible for the dissemination of findings to the users. As previously emphasized in this paper, participants strongly believed that to ensure the clarity and dissemination of study results for the largest possible user community, state and local representatives should be involved in the loss study process from its inception.

CONCLUSIONS AND RECOMMENDATIONS

The user needs subpanel concluded that some previous loss studies may not have sufficiently taken into account state and local users.

This lack of attention and focus has manifested itself in studies having a geographic focus and an inventory data base that do not easily permit utilization at the local level. In addition, reports have been too technical to be readily understood by users. The earthquake scenario on occasion has produced loss estimates that lacked credibility and hence were not useful for planners or policymakers. Too often it seems the producers of loss studies have incorrectly identified other producers of loss studies as being the users of their studies. Too often users have neither received the types of information they thought they were to obtain, nor have they received reports they could understand and disseminate easily.

Data assembled from workshop discussions and the survey form the base on which the panel has based its recommendations. It is important to reiterate that these data may not reflect the needs of the larger state and local government user communities. The panel believes, however, they are suggestive of those needs. Within the methodological limitations discussed earlier, the following recommendations are offered.

1. Producers of loss estimation studies should involve their state and local clientele (the users) in the entire loss estimate study process.

Loss estimation should and can be a vehicle of understanding the risk and potential losses from earthquakes. Therefore, the process by which such studies are conducted becomes more important than the actual results. The involvement of state and local users in the entire process of loss estimating will increase the likelihood that these important actors come to understand not only the manner in which the study is carried out but also the nature and extent of the seismic problem. Their involvement will facilitate the utilization and dissemination of the findings as well as the use of such studies for the purpose of advocating greater emphasis on seismic policy.

2. Loss estimate studies should clearly indicate the level of potential error in the estimates as well as the confidence of the producers of the estimates for the various components of loss estimates.

A consistent workshop theme among users was the desire for credible loss estimates. The state of the art in such studies is not well advanced, and predictions of loss may be in error by a factor of 10. The user community needs to understand where error in prediction is most likely. In addition, it is important for the user community to be able to specify where the most accurate information is needed and to know what accuracy is possible. When additional expenditures may result in lower error factors, this information should be presented. It is also relevant when deciding if the information is sufficiently valuable to warrant additional resources.

3. Producers of studies should build an inventory base for loss estimates that can be disaggregated to the smallest political and geographical unit.

State or regional loss studies must present sufficient information for local planning, preparedness, and mitigation activities. By compiling inventory data so that they can be disaggregated and accessed by local units, producers will provide the opportunity for smaller units to use their studies. Furthermore, the computerization of data would permit updating and multiple use. For example, if a loss study identifies "suspect" buildings in a regional area, each locale could be provided a list of these buildings and their locations to determine if local action is warranted.

4. Loss estimate studies should contain a scenario earthquake that is relatively probable and yet large enough to cause serious losses. Loss estimates should be provided for different seasons and times of the day.

This recommendation is consistent with findings from workshop discussions and survey instrument results. About 70 percent of the users indicated these types of information are essential for planning purposes.

5. The producers of loss studies should determine the importance to users of the estimates of loss to different types of structures and functions. In addition, the importance of the certainty and reliability of the different estimates to the users should be identified, and the studies should be oriented toward these needs.

The users at the workshop ranked the importance of 19 different structures and functions and indicated how reliable loss estimate predictions should be for each structure and function. It is important to remember, however, that these rankings are only suggestive. Ideally, state and local decision makers who are involved in the loss study from its inception can provide producers with more refined definitions of their needs.

6. The dissemination of loss study findings should have greater

emphasis. State and local users of such studies should be responsible for dissemination to relevant agencies and the public.

Previous dissemination of studies appears to have been unsatisfactory, and there is some indication that the dissemination process has been a barrier to utilization. To increase the likelihood of access and use the reports should be as nontechnical as possible. Methodological discussions should be included in appendixes. More emphasis should be placed on the implications of the findings for seismic planning and policy adoption. The loss study reports must be aimed at the audience of users and not other producers. Methodological appendixes will provide the information necessary for replication and validity checks. But the thrust of the report must be concentrated on those who will apply the findings—the users.

Working Paper C
Characterization of Earthquake Hazards for Loss Studies

Technically, earthquake hazard or seismic hazard refers to the direct impact of an earthquake on the earth, including ground shaking, ground failures (liquefaction, surface faulting, landslides, and settlement), and the water-related phenomena of tsunamis and seiches. In this usage, the characterization of earthquake or seismic hazard does not include effects on the humanly constructed environment. Thus, threats such as collapsing buildings, overturning shelving, or breaking gas lines which in common language are often called earthquake hazards, or which are encompassed in the National Earthquake Hazards Reduction Program, are not topics in this working paper.

This paper describes earthquake hazards and how they can be quantified, reviews current practice in the specification of hazards for loss studies, and describes a range of hazard specifications that might be used in future loss studies.

TYPES OF EARTHQUAKE HAZARDS

The primary and most pervasive hazard associated with earthquakes is the shaking of the ground. This causes direct damage to structures as well as physical phenomena (seiches, liquefaction, and landslides) that can result in significant damage and loss. Ground shaking is generally caused by the release of crustal energy by rupture along a fault surface. Sometimes the rupture reaches the earth's surface and is evident after the event, but often the rupture is buried beneath surficial sediments and rocks. Volcanic earthquakes are less common, tend to be limited to moderate magnitudes, and are primarily caused by thermal rather than mechanical action.

The energy released by a rupture propagates in the form of compressional waves and shear waves. The character of ground motion from these waves is a function of the source characteristics of energy release, the attenuation (damping) characteristics of the earth's crust along the wave travel path, the near-surface geologic characteristics that may modify the frequency content of the motion (amplifying certain frequencies and damping others), and the interaction of the body waves with the earth's surface to form surface waves.

Collateral earthquake hazards caused by ground shaking include seiches, liquefaction, and landslides. These hazards can lead to complete destruction of structures. For example, the Niigata earthquake of 1964 led to the liquefaction of soil in a large area, causing the loss of foundation strength for many apartment buildings. As a result, buildings tilted by as much as 70 degrees. A recent report of the National Research Council (1986) summarizes the state of the art of estimating the hazard from liquefaction. Landslides constitute a similar, shaking-induced hazard. In the 1964 Alaska earthquake, landslides in Anchorage caused the destruction and total loss of many residences and buildings. Landslides into bodies of water, or on the bottom of harbors and bays, can produce water waves that may cause very serious losses.

Another hazard associated with earthquakes is rupture of the earth's surface caused by displacement of a fault. In the United States this phenomenon is generally observed only in the western states and Alaska. The fault movements associated with great earthquakes may be on the order of 5–10 meters. Such deformations are difficult or impossible to design for, and the best policy may be to avoid fault locations entirely.

For some civil engineering works (e.g., pipelines, transmission lines, highways, railroads, and aqueducts) it is not possible to avoid fault crossings. In these cases the hazard to the facility can be identified and quantified, and the effect on the system's function can be evaluated. If the system damage and its probability of occurrence are not acceptable, alternative system designs are usually possible to alleviate damage to components crossing faults (e.g., designing redundant links in the system, designing the fault crossing to be easily repairable, or devising an earthquake response plan that reduces the functional loss).

Still another earthquake hazard is a tsunami, which is a wave generated in the open ocean as a result of tectonic movement of the floor of the ocean. Where such waves come ashore, they can rise to significant heights and cause considerable damage. Tsunamis are a potentially severe problem for Alaska, and tsunamis generated by Alaskan earthquakes have also caused damage to the West Coast states. Tsunamis generated both in Alaska and Chile have caused great destruction and fatalities in Hawaii. Apparently tsunamis are not a problem along the Atlantic and Gulf coasts, but may be a threat in Puerto Rico and the Virgin Islands.

SCOPE OF EARTHQUAKE HAZARD ASSESSMENT

The purpose of assessing earthquake hazards is to identify and quantify the severity of the various hazards in the geographic area of interest for the loss estimation study, given a scenario earthquake. In most cases an estimate of the frequency in time (or probability of occurrence over a given period of time) of the hazard is also necessary. The results of the hazard assessment are combined with the ground-motion and damage relationships and the inventory of facilities in the study region to produce estimates of losses.

Assessing earthquake hazards and specifying the other inputs to a loss study are related but independent activities that can be undertaken by different investigators at different times. One advantage of this independence is that various parts of the analysis can be updated (e.g., more recent data from a U.S. census can be incorporated) without having to reinvestigate other inputs to the analysis. Also, studies of facility inventories and vulnerability relations can be locally or regionally undertaken, while nationally developed seismic hazard data (e.g., studies by the U.S. Geological Survey) can be produced separately. The converse division of labor is also possible, as when national inventory data (e.g., census data on housing) is combined with seismic hazard studies locally undertaken by state or local government geological agencies or local geotechnical consultants.

Earthquake hazards and other inputs to loss estimation are related in that the hazard must be specified in terms that are meaningful to the vulnerability analysis. For example, if the seismic hazard is specified in terms of the peak acceleration during the earthquake, the vulnerability functions cannot be given using a qualitative intensity scale such as MMI. If either the hazard or vulnerability analyses must be translated to make it compatible with the other, care must be taken in the translation, and the conversions used must be fully documented.

Simple empirical correlations based on observed statistics often lead to incorrect results in particular applications. Simple representations of the shaking hazard, for example, those using peak acceleration or Modified Mercalli Intensity (MMI), are attractive because hazard analyses are frequently available for these parameters, and vulnerability functions are available to estimate losses for them for many types of structures. The price for this simplicity is a wide range of uncertainty in the damage and loss, because simple representations of seismic shaking or earthquake-caused ground failure cannot capture the details of the underlying phenomena.

More complex representations of ground shaking, for example, through a filtered "effective" peak motion, a single-degree-of-freedom linear response spectrum, a nonlinear spectrum, a time history of motion, and the duration of strong shaking, have the ability to be more accurate predictors of damage and loss. There is less agreement, however, on how to estimate these functions for a future earthquake, how to quantify the single- or multidimensional hazard associated with them, and how to derive an accurate predictor of damage from them.

CHARACTERIZATION OF GROUND SHAKING

For historical and pragmatic reasons, MMI has been used as the ground-shaking measure in most earthquake loss studies conducted in the past, and likely will remain the standard for studies in the near future. This procedure was popular in early loss studies because multiple, instrumental records of ground shaking were not available to correlate motion levels to damage. Even today, records of strong shaking at the site of buildings damaged during earthquakes are rare, whereas assessments of the MMI level at that site can always be made by an experienced investigator. The MMI assessment denotes the severity of earthquake shaking at a particular location in terms of the effects on people, on construction, and on the earth's natural features. The MMI level depends on seismic, geologic, engineering, and human factors. The assigned MMI value for a particular earthquake and location is a qualitative measure of the integrated response of the natural and man-made environments to earthquake energy.

As Richter (1958) also notes, at the higher intensity levels (MMI = X, XI, XII) the scale refers primarily to ground failure rather than directly to ground vibration. The primary fault trace phenomena and secondary ground effects depend on the type of faulting motion (vertical versus horizontal), the duration of the faulting movement, and the nature of the ground in the immediate vicinity of the fault. Ground failures such as liquefaction, faulting, and landslides are not good measures of ground shaking since they can occur at low as well as high levels and durations of ground motion.

Contrary to conventional seismological practice and to previous applications in the loss estimation field (e.g., ATC-13), it is desirable to use MMI intensity as follows: First, ground failure phenomena should be treated separately from ground shaking, and second, only intensities below MMI XI should be used to describe the severity of ground vibration. This does not imply that quantitative measures of ground vibration (e.g., peak ground acceleration or velocity) are limited to a maximum value that would correspond, according to one of the various MMI-acceleration or MMI-velocity relationships proposed, to MMI X. In other words, MMI X is not necessarily the maximum severity of ground shaking that could occur on earth. As a general rule, the estimation of MMI can rarely be refined beyond a ± 1-unit range.

When making loss estimates, the effects of soil conditions on intensity of shaking must be considered. One means of accomplishing this, if ground motion is used as an intermediate variable to estimate losses, is to modify the estimates of ground motion (e.g., MMI) to reflect the expected effects of soils at locations in the region from the hypothesized earthquakes. Table C-1 presents one set of correction factors that has been proposed for southern California and that attempts to account for both the type of rock that might underlie a site, and the depth to the water table (Evernden and Thomson, 1985). Other correlations may have equal or greater justification, depending on the data base and the region of study.

The use of MMI in loss estimates is a gross simplification that is justifiable only if more precise methods are not available. It is known, for example, that modifications of earthquake ground motions by soils are frequency dependent. Therefore, an accurate modification of ground motion should consider the frequency characteristics of the structures for which losses are to be estimated. Similarly, explicit

TABLE C-1 Ground-Motion Correction Factors for Southern California

Geologic Condition	Change in Intensity
Quaternary alluvium (water table > 100 ft)	0.0
Quaternary alluvium (water table 30-100 ft)	+1.0
Quaternary alluvium (water table < 30 ft)	+1.5
Sedimentry rock	0.0 to -1.6
Volcanic, granitic, and metamorphic rock	-1.7 to 2.0

SOURCE: Evernden and Thomson (1985).

quantification of the effects of earthquake magnitude, distance, and duration are ignored when MMI is used. For example, an MMI VII observed at the epicenter of a magnitude 5 earthquake does not imply the same ground motion as an MMI VII observed (for the same soil conditions) 100 km from a magnitude 7 (Murphy and O'Brien, 1977). For these reasons, use of MMI (and similar intensity scales) should be recognized as a less-than-perfect representation of earthquake ground shaking to be used only until more precise parameters and methods are available.

HAZARD AND LOSS ESTIMATION PROCEDURES

Scenario earthquakes have been determined following rationales that in different ways express the need to compromise between the likelihood or credibility of the event and its destructive potential. Once the scenario event has been selected, all existing large-scale loss estimation procedures use deterministic relationships to calculate the level of ground motion at each site, the resulting damage, and the losses.

Occasionally, some of the relationships (most notably the relationship between ground-motion intensity and damage) include uncertainty, but in no study has uncertainty been propagated through the analysis to produce probabilistic estimates of loss. For the treatment of uncertainty, one can therefore regard all previous large-scale, general-purpose loss estimation methods as "deterministic procedures under scenario earthquakes." This type of analysis reflects

TABLE C-2 Applications of Loss Estimation Methods

Applications	Appropriate Methods
Advocacy	A,B
Response planning	A,B,D
Preparedness planning	A,B
Mitigation strategies	A,B,C
Relocation/recovery	E
Risk evaluation	B,C
Economic impact analysis	B
Insurance	A,B,C,D,E
National security	B,C,D

KEY: Current practice: A = extrapolation from historical data; and B = scenario analyses and accuracy estimates. Emerging methods: C = loss-frequency analysis; and D = simulation of actual events with variability. E = cumulative over time.

the heritage of early loss estimation efforts. Resistance to change has resulted from the difficulty of more complete representations of uncertainty and by computational constraints.

Deterministic scenario-type analyses are easy to interpret and will likely remain the basic type of earthquake loss calculation in the near future. However, they are not ideal for all purposes because they are not capable of fully representing uncertainty and because of the lack of a clear rationale for selecting scenario earthquakes. For certain uses, deterministic scenario analyses are actually inappropriate, and alternative methods, not yet fully available, must be developed. A listing and brief description of loss estimation procedures (some existing, others in need of development) and an indication of their potential uses follow. Appropriate applications of each are shown in Table C-2.

Extrapolation from Historic Losses

Loss information from historical events in the region of interest can be adjusted to reflect recent changes in the inventory and differences between characteristics of the scenario earthquakes and those of the historic events. This analysis is simple and inexpensive, but typically less accurate and less general than analyses based on models of ground motion, damage, and loss. Such a technique is appropriate when a historic event, not much different from the scenario earthquake of interest, has occurred in the recent past, as in the case of the largest of the six scenario earthquakes used in the National Oceanic and Atmospheric Administration's San Francisco study (Algermissen et al., 1972). This condition, however, seldom applies.

Selecting a historic event as the basis for a loss study does not avoid the problem of uncertainty, although the nontechnical audience is less likely to bring up the issue of uncertainty because of the intuitively convincing nature of events that have happened before. Results of analyses of this type are illustrated in Figure C-1a.

Scenario Analysis with a Statement of Accuracy

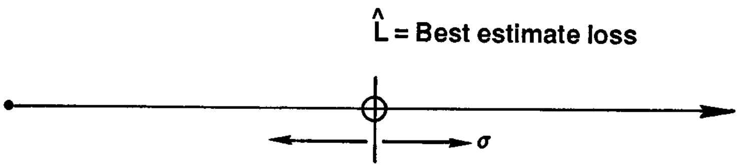
This type of analysis is most often used today, although often without the accompanying statement of accuracy. One or more earthquakes are selected, based on criteria reviewed earlier herein, and single-value estimates of the resulting losses are produced. Accompanying these estimates with even simple but objective statements of certainty would prove useful to the users. For example, one might use sensitivity analysis: each major input parameter or relationship is modified in turn and the analysis is repeated to calculate the effect of the change on the calculated losses. The amount by which each input parameter is modified should reflect the degree of uncertainty on that parameter. The results of such an analysis are similar to the "type A" seismic hazard analysis (Figure C-1a), but a description of uncertainty in the estimates for the scenario event may be included.

Historic Maximum Earthquake

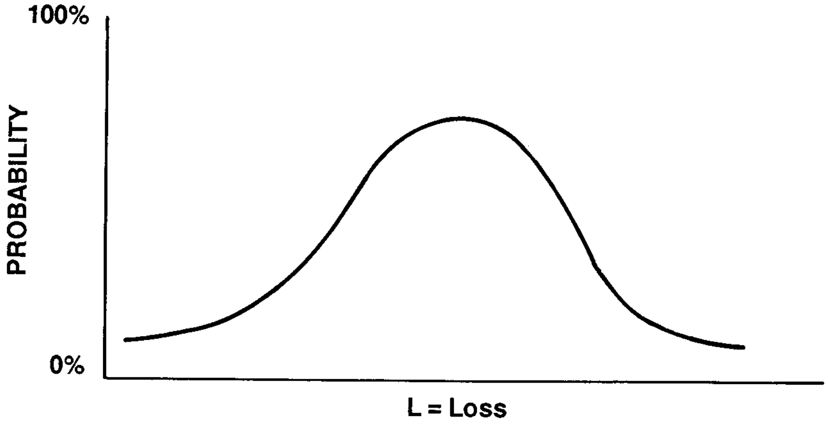
Historic earthquakes, when judged to be suitable and perhaps with adjusted magnitude, intensity distribution, or location, can be used in loss estimation studies. These earthquakes are convincing to both the users and the general public.

Recurrence Rate Earthquake

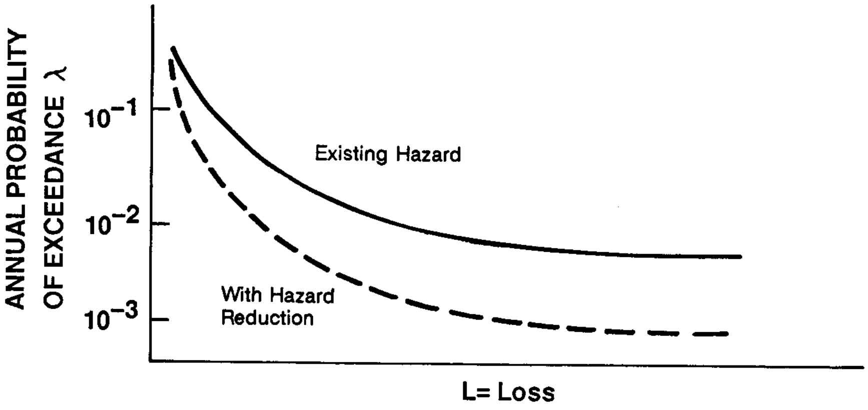
This can be an appropriate selection technique when a known seismic source zone or fault dominates the problem at hand, for example, the Wasatch Fault at Salt Lake City, Utah. In such a case, an earthquake magnitude may be selected on the basis of its recurrence rate, that is, from the magnitude-frequency law ($\log N = \mathrm{a} - \mathrm{b}M$). N



(a) HISTORIC LOSSES OR SCENARIO EARTHQUAKE



(b) PROBABILISTIC



(c) LOSS-FREQUENCY ANALYSIS

FIGURE C-1 Form of results of different loss estimation techniques.

is the number per unit time of earthquakes exceeding magnitude *M,* and a and b are coefficients typically estimated by statistical analysis. For example, the magnitude of earthquake expected to occur on the average once in every 100 or perhaps 500 years or more might be selected. The location of the earthquake can be defined to maximize damage or loss. This method is more difficult to apply in an area of diffuse seismicity in that the location(s) of the seismogenic tectonic structures are not well constrained, as in much of the eastern United States. However, even in those areas, it is possible that the recurrence rate method could be a viable approach for some problems.

Geologically Defined Characteristics

This method is also most applicable to regions where the tectonic regime and the seismogenic tectonic structures are well known. Earthquake magnitude and location are determined on the basis of geologic and seismologic parameters that have been specifically associated with a given fault or area, for example, slip rate, stress drop, and typical fracture directions and lengths. Locations where this criterion might be applied are Pallet Creek and Anza, California, because of the ability of geologists to define the characteristic fault behavior at these places.

Forecasting

Based on past seismicity as well as relevant physical premonitory considerations, specific earthquake forecasts can sometimes be made. Such forecasted events (earthquake predictions) might then be used as scenario earthquakes. Regions of the United States where earthquake prediction efforts are under way include the Aleutian Islands and central California (Parkfield).

Maximum Credible Earthquake

This and similar undefined criteria have sometimes been used in the past, but such concepts are vague and should be avoided in favor of more objective criteria.

Loss-Frequency Analysis

This loss estimation procedure is very different from the previous two methods (extrapolation of historical losses and scenario analysis).

Its objective is not to estimate earthquake losses under a single postulated event, but to calculate the frequency with which various levels of loss are exceeded in the region of study. It is important to realize that a particular loss may result from earthquakes of different characteristics, for example, from a nearby earthquake of moderate size or from a distant earthquake of larger magnitude. This procedure sums up the contributions to the frequency with which any given loss is exceeded from all possible earthquakes, large and small, near and far away. The final result is a plot of the annual probability of exceedance versus loss (loss-frequency curve), as shown in Figure C-1c.

From an operational point of view, the analysis proceeds as follows: discrete ranges of possible magnitudes and locations are selected and a frequency of occurrence is assigned to each magnitude-location combination. The loss produced by each combination is then estimated using a procedure similar to scenario-earthquake analysis and the results of all such loss calculations are summarized through the loss-frequency curve. (A mathematical formulation of this method is given later.) The major departure from existing scenario-type analyses is that, in loss-frequency calculation, one would typically regard the loss from a given magnitude-location combination as a random variable, due to the uncertainties of predicting ground-motion intensity, physical damage, and economic and human losses.

The mathematical procedure for this type of analysis follows closely the method of probabilistic seismic hazard analysis described in a report authored by the Committee on Seismology, National Research Council (1987). Described here is the specific application of these probabilistic concepts to derive estimates of losses and their frequencies of occurrence for a region or metropolitan area.

Procedures are well established for estimating the probabilities of seismic ground motion at a point. Three types of input are required: (1) a designation of faults or sources that generate earthquakes and the distribution of earthquake locations on the faults or sources, (2) a description of the distributions of earthquake sizes (magnitude*) and times of occurrence for each fault or source, and (3) a function that estimates the intensity of ground motion at the site, for earthquakes of specified magnitudes and locations on the faults or sources. With

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*It is essential to be clear as to which magnitude scale is used.

these three inputs, probabilities that a specified amplitude of ground motion a will be exceeded at the site per unit time can be calculated. The total probability theorem is used for this calculation:

$$P(A > a)\text{time} \simeq \sum_i \nu_i \int_m \int_r P[A > a|m, r] f_{M,R}(m, r) dmdr. \quad (1)$$

In equation 1, $P[.]$ indicates probability, the vertical bar ($|$) indicates conditions, $f(.)$ is probability density, the summation is over all sources, i, that might produce ground motions affecting the site, ν_i represents the expected number of earthquakes per unit time in source i, and m and r are general descriptors of earthquake size (e.g., magnitude) and location with respect to the site (e.g., distance). The approximation in equation 1 results from using the expected number of earthquakes rather than calculating probabilities of multiple occurrences and from neglecting the effects of multiple exceedances of amplitude a. For the usual annual probabilities of interest this approximation is very accurate. The formulation of seismic hazard considers (and integrates over) all earthquakes that can affect the site. The resulting annual probability is calculated, in effect, by weighting all these earthquakes by the ground motion that they may produce at the site.

Practical applications of seismic hazard analysis are accomplished in several steps, which lead to the calculation of equation 1. An illustration is given in Figure C-2. First, earthquake faults or zones of seismicity must be delineated; from these, the distribution of distance $f_R(r)$ between earthquakes and the site is obtained. Next the probability distribution of earthquake magnitudes $f_M(m)$ is derived for each source or fault, often by analysis of historical earthquakes that are spatially associated with that feature. The product of these two distributions is $f_{M,R}(m,r)$ in equation 1.

The third specification concerns the ground motion occurring at a site, which is a distribution of ground-motion levels conditional on earthquake magnitude, distance, and local geology. This distribution allows calculation of the probability $P[A > a|m,r]$ in equation 1. The equation that calculates a mean or median ground-motion level as a function of m and r is often termed an attenuation equation. The final step in the process consists of integrating over all earthquake magnitudes and distances, in the manner of equation 1, to calculate hazard results for various ground-motion amplitudes, as illustrated in Figure C-2d by a typical hazard curve.

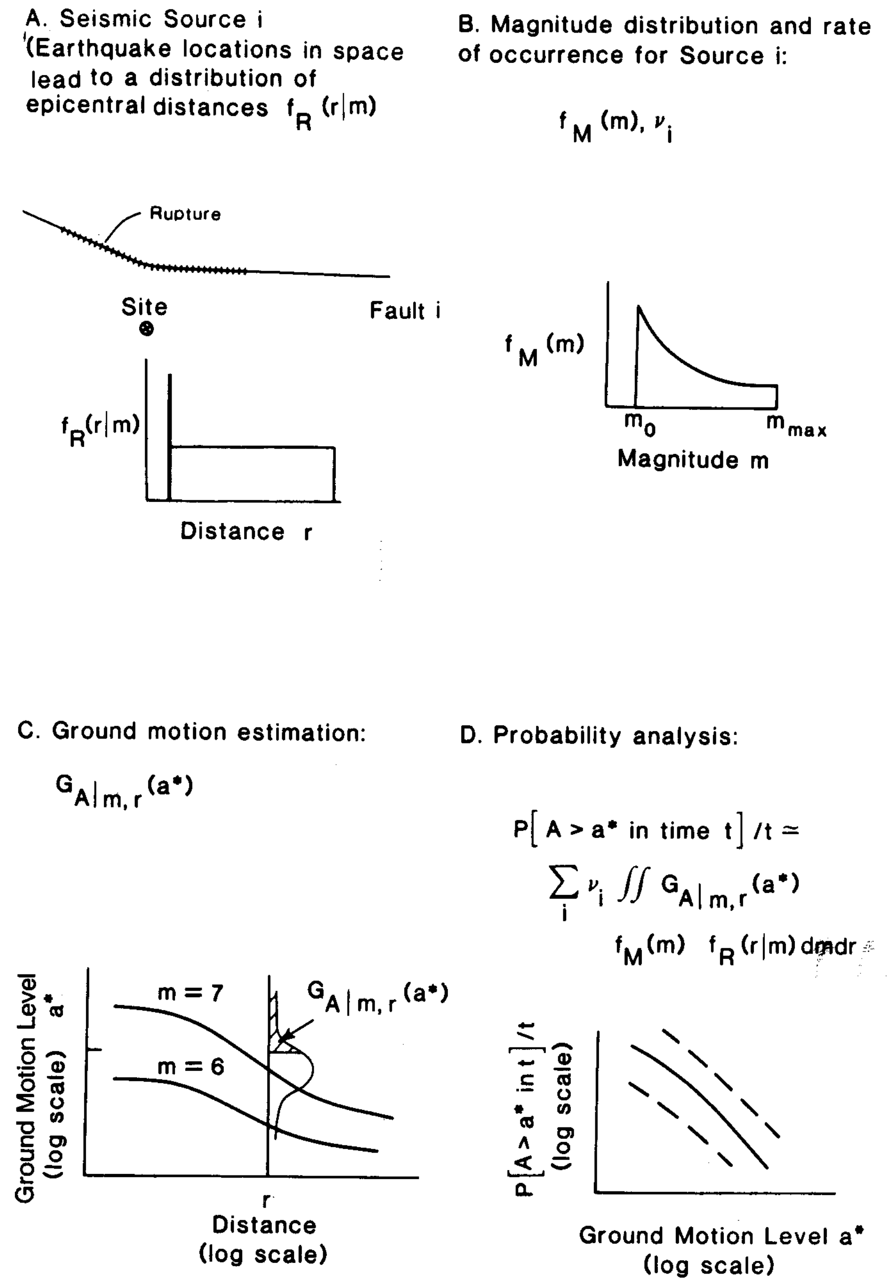

FIGURE C-2 Graphs indicating probabilistic seismic hazard analysis steps. Source: McGuire (1987).

A similar procedure can be applied to calculate annual probabilities of earthquake losses from earthquake ground shaking in a region, but additional information is needed. First, a scalar variable needs to be chosen to represent the potential losses (e.g., dollar loss or number of deaths). Second, the correlation of ground motion at different sites must be taken into account. This correlation results because separate sites may be affected simultaneously by the same earthquake, by similar focusing effects of the source, by similar travel paths, and by similar geologic conditions at the site. Just as the uncertainty in ground motion is important in site hazard calculations, $P[A > a|m,r]$ in equation 1, correlation of ground motion at multiple sites is important to regional risk estimates. The estimation of annual probability of exceeding a loss $\$'$ for the region can then proceed by an enumeration of all earthquakes that might affect the region:

$$P[\$ > \$'] \simeq \Sigma\nu_i \int_m \int_r P[\$ > \$'m, r] f_{M,R}(m,r) dmdr, \qquad (2)$$

which is similar to equation 1 except that the summation is over all earthquakes that may affect the region of interest, and R represents earthquake location (without reference to a particular site). The conditional probability in equation 2 is evaluated as:

$$P[\$ > \$' \mid m,r] = P[(\sum_j \$_j(x_j, y_j)) > \$' \mid m,r], \qquad (3)$$

where $\$_j(x_j, y_j)$ is the loss at location x_j, y_j and the summation is over all locations in the region. The correlation of ground motion enters into this calculation of total loss over all locations in the region for an earthquake of specified size and location. In practice the region is divided into convenient units (e.g., census tracts, statistical areas, or blocks) for this enumeration. The available format for the facility inventory or census information obviously plays a role in choosing the appropriate size of subdivisions for estimating total losses.

Several simplifying assumptions are usually made in applying equation 2 to estimate earthquake losses. Often the uncertainty in earthquake losses during a hypothesized earthquake is ignored, leading to a great simplification of equation 3. These uncertainties may result from variabilities in the ground motion generated at the site (whether or not this is used as an intermediate variable), the effect of local geology on ground motion, the loss that might be generated in specified facilities for a given ground motion, and the number and type of facilities at a given location (e.g., uncertainty in the facility inventory). Ignoring these uncertainties constitutes a simplification that may be justified if, for example, only a best estimate of losses versus annual probability is desired, but in this case the statistical mean of all relations (rather than, for example, the median) should be used. Even then the results only approximate the mean loss, and they are likely to underestimate it, perhaps substantially.

Other simplifying approximations are appropriate under certain conditions. If the region considered for the loss estimate is rather small (several tens of square kilometers), the integration over locations in the region can be avoided by assuming that the entire region is subjected to the same ground motion. Then, an accurate hazard analysis can be performed for one point (e.g., the geographical center of the region), and the seismic hazard results can be translated to loss estimates. In effect, this assumes that the region is small enough that the same ground motion occurs over its entirety.

In some parts of the United States, the earthquake hazard results from specific fault zones or sources that are small relative to the size of the area that could be affected, for example, the New Madrid fault zone. In these cases the earthquakes occur in an area that is small relative to the region that may be examined for loss calculations, for example, the Mississippi Valley. The loss (more specifically, the range of losses) calculated for a specific magnitude earthquake occurring in the fault zone can then be associated with the annual probability of that event, using the recurrence relation for earthquake magnitudes in that source. In effect, one avoids the integration over location in equation 2; the 1,000-year earthquake is used to estimate the 1,000-year loss. Note that this circumstance does not by itself justify ignoring uncertainty in the resulting losses; as a minimum, mean values (rather than medians) should be used in all relations to calculate the resulting losses.

Simulation of Actual Events

In this typical analysis, all of the uncertain input parameters, except possibly for earthquake magnitude and location, are numerically simulated. Hence, for each given earthquake magnitude and location, different loss scenarios are generated in different simulations. The results are patterns of damage and loss, which are more realistic than those produced by best-estimate scenario analysis. Figure C-1b illustrates results of this type.

Cumulative Loss Over Time

For applications that depend on the total loss that may be expected in a certain geographical region over a given time period, one should sum losses due to future earthquake occurrences in the region. One use of this result would be to compare earthquake risks with risks from other natural phenomena. For certain uses, one may need only the expected (actualized) cumulative loss, whereas for others it may be important to calculate the entire probability distribution of the cumulative loss.

SUMMARY

This description of loss estimation methods is neither exhaustive nor exclusive, meaning that certain applications may require the development of specialized procedures not included in the present list or the combined use of several methods. Generally speaking, deterministic scenario analyses can be made at a level of detail and spatial resolution that is impractical in probabilistic risk calculations, because of the large number of calculations required by the latter methods. Hence, deterministic analyses (methods A and B as described in Table C-2) might be ideal tools for use in disaster exercises and for the detailed evaluation and improvement of loss reduction strategies. On the other hand, public safety policies (such as the selection of suitable building code provisions) and economic decisions would be best made considering the integrated results of risk studies (method C).

The usefulness of scenario type analyses may vary geographically. For example, in regions where events of size close to the maximum possible magnitude occur frequently, a single-event analysis using one such event may be all one needs to make informed decisions. By contrast, in regions where seismicity is low and the maximum earthquake size is unknown, the earthquake threat may be dominated by events in an intermediate magnitude range. In the latter case, one should make decisions based on the projected loss from a variety of earthquakes, considering the frequency with which each type of event occurs in the area.

For many uses, a fully probabilistic risk calculation by method C is the ideal type of analysis. For example, knowledge of the risk curve would allow quantitative assessments of public safety with respect to earthquakes and comparisons with other risk sources. Insurance and financial institutions would find risk curves appropriate for the evaluation of expected (long-term average) profits as well as for the evaluation of the frequency of catastrophic losses. Another example is the comparison of risk reduction options: different risk reduction or preventive actions might have different effects depending on the earthquake size and the amount of damage. The effectiveness of each proposed action could then be represented in terms of the downward shift that a particular action produces on the original risk function, as shown by the dotted curve of Figure C-1c. Method D (repeated simulation) is perhaps most appropriate to plan emergency response, when one needs to evaluate the adequacy of response strategies in the context of certain damage and loss scenarios.

Working Paper D
Inventory of Facilities

This paper addresses the inventory problem. It limits the term inventory to the task of listing man-made facilities and their attributes, rather than the parallel task of producing an inventory of the attributes of different soil types or other geologic data, which is a seismic hazard analysis task. Structures other than buildings, such as lifeline facilities, can be inventoried similarly as for buildings, although the information sources and data collection techniques vary. Most major lifeline facilities are already inventoried to some extent by their owners, and it is the more difficult problem of conducting an inventory of buildings that is the focus of this paper.

The number of buildings and other structures in the study area of most large-scale loss estimation studies is great. The earthquakes selected as the planning basis for large-scale loss estimation studies can be strong enough to shake 5,000 or more square miles, and the study area of most interest often contains a population of several million. Pre-existing files or data bases do not contain the amount or quality of information that is desired for the purpose of estimating earthquake losses. Inventories used for earthquake loss estimation purposes must be developed in a highly selective manner because this is the most time-consuming and costly step in the loss estimation process. Thus, the inventory task is often a matter of using the data that can be collected and organized within the budget allotted, rather than developing the ideal inventory.

The losses of concern may be facilities damaged or rendered dysfunctional, dollar losses to facilities or dollar value of lost production, casualties, or homelessness. The kind of loss information sought is a determinant of the kinds of inventory information needed in the analysis. Hence, the types of loss to be estimated must be specifically defined prior to selecting an inventory method.

Theoretically speaking, a unique and all-purpose inventory might be created, but its contents would include so many descriptors and other items of information that it would not be feasible to assemble. Moreover, given the lack of understanding about motion and damage or ground failure and damage relationships and the prospect that this understanding will improve in time, the chances of anticipating all relevant inventory data today for some future use are, indeed, slim. Efforts to create an exhaustive inventory of information about facilities would be a misguided, ineffective effort.

HIERARCHY OF DATA

Based on recent loss estimations prepared by different methods and people, the best hierarchy of data items seems to be:

- Facility location (addresses are preferred for buildings and structures, but they are often listed only by zip code or census tract; the census tract or other appropriate zone is used for linear or areawide facilities);
- Type of structure;
- Material(s) of construction (for the load-carrying system);
- Height (for buildings);
- Floor area (for buildings);
- Date constructed;
- Value (market or replacement value adjusted to a selected base year);
- Use of facility (occupancy or social function); and
- Number of people in facility at different times of day and season.

Many other data might be added that, based on present knowledge of earthquake effects, could improve the accuracy of loss estimates. Among these (not necessarily in order of importance) are:

- Type of foundation system;
- Configuration of facility (in plan and in elevation or section);
- Special-damage control features of facility;

- Code under which facility was constructed; and
- Nonstructural features or contents with special fire or hazardous materials characteristics.

Nevertheless, no loss estimates are possible without certain basic information about facilities. Further, some kinds of inventory information are common for all loss estimation methods, that is, facility location, construction classification, occupancy data (number of occupants and type of occupancy or use), and facility property value. According to current procedures, this information is assembled (inventoried) by (a) field observation or sampling, (b) review of other previously assembled records for a given community, or (c) extrapolation from conveniently available records to the end-form construction data desired, such as by inferring floor area from number of employees or land-use acreage figures, degree of earthquake resistance incorporated in the design from date of construction, or value from floor area.

When other economic losses are to be estimated, additional inventory information is needed, especially the facility's economic use, or "social function" in the terminology of ATC-13 (Applied Technology Council, 1985), and facility contents. Economic relationships that are not a part of the inventory also must be modeled.

Essential inventory information can be assembled in several ways, and no single inventory method can be recommended. However, two major alternatives discussed in this paper are (1) the NOAA-USGS method of field observation, coupled with input from local building experts, land-use patterns, and census data, and (2) the FEMA/ATC-13 method, which would use existing detailed construction class inventories where available but in practice would generally rely on extrapolations from economic data to impute almost all construction characteristics.

The most important attributes of facilities other than buildings seem to be unique to the type of facility and are not addressed herein. For example, while underground pipelines can be treated in a parallel manner to buildings in classification systems, the general headings have very different meanings. The size of a pipeline would probably mean the diameter of a pipe, while for a building it would mean the square footage or height. The types of materials used for pipes are also different from buildings.

DISCUSSION OF ESSENTIAL DATA

The following subsections discuss three aspects of the data required for essentially every study.

Construction Classes

The most frequently used approach to developing an inventory of building construction characteristics is the construction class method. Once the facilities are described in terms of their location and construction class, and after construction classes are tied to motion-damage-loss relationships, this overall vulnerability analysis can be combined with the seismic hazard analysis to predict damage.

Table 3-1 presented an example of a typical construction class system (see Chapter 3). Developed by the Insurance Services Office (ISO), this scheme has been widely used for insurance as well as noninsurance loss estimation purposes. Once the difficulties of properly counting buildings and assigning them to the appropriate class are overcome, relationships between shaking intensity and resultant damage are used to project damage (see Working Paper E).

The degree of approximation present in this approach is typical of earthquake loss estimation studies. It is very expensive to collect precise data about construction characteristics, and these data are not already tabulated in inventories prepared for nonseismic purposes. Although this scheme may seem to categorize the building stock rather coarsely, it is usually more than precise enough to match the accuracy of the inventory work.

The extreme case of what might be called a detailed inventory is the information an engineer collects concerning materials properties and geometric data on each structural member and connection in a building for the purposes of new design or an evaluation of a building's earthquake vulnerability. This "inventory" is then subjected to detailed load and capacity calculations to design an adequately strong and stiff structure or to see if the existing building is adequately earthquake resistant. Even when an inventory of this detail is collected for a single building, the estimation of earthquake damage that would result from a specified earthquake is still an approximation. Thus, while it is true that the better the inventory the better the accuracy of the resulting loss estimates, it is also true that even with a perfect inventory there would still be a large amount of approximation inherent in the process of estimating the losses that might occur in future earthquakes.

A discussion of the extent of building stock inventory information already available for earthquake loss estimation purposes will be found in work conducted at Cornell University (Jones et al., 1986) and by the Association of Bay Area Governments (ABAG) (Perkins et al., 1986). A rough estimate of the field work required in the ABAG project to survey commercial or industrial areas is that about five census tracts per day can be "windshield" surveyed from a slowly moving auto with a two-person team.

The study by Gauchat and Schodek (1984) is innovative for its use of aerial photo analysis, although it restricted itself to housing because the construction characteristics of housing are easier to observe in this way; commercial and industrial building construction characteristics are more varied and less easily observed from the exterior. In a study of Los Angeles County earthquake losses by Scawthorn and Gates (1983), except for construction data on high-rise and unreinforced masonry buildings, inferences were used to convert land-use maps showing acreage of various uses into 13 construction classes and into building areas. A committee of engineers, building officials, and realtors was relied on for these extrapolations.

The NOAA-USGS studies also capitalized on existing files concerning high-rise or other special categories of buildings, used census data to inventory most of the housing, and relied on field sampling of commercial-industrial areas coupled with land-use maps and local engineering knowledge of typical construction patterns.

Occupancy

When life safety impacts of an earthquake are to be estimated, as is almost always the case except for insurance or other property loss studies, the number of occupants in buildings must be estimated. Once the damage to a class of construction is estimated, the percentage of occupants or passersby who would be slightly or seriously injured, or killed, is estimated. This allows for the number of persons to be multiplied by this ratio to produce estimated casualties. Another approach used instead of or in combination with this method is to apply a casualty ratio to the overall population of an urban area.

The number of people who would be outside of buildings must be estimated because for some classes of construction, notably unreinforced brick buildings, the collapse of at least some brickwork off the outside the building to the sidewalk or other exterior area is more likely than complete collapse.

The time of day must be taken into account. In many areas of the United States, people work, shop, and engage in other daytime activities in buildings that are on average more hazardous than the residences where they spend the night. Estimating losses for different times of day is typical of loss studies for this reason. Fortunately, census data, planning department studies or economic data, and reliable inferences relating the number of occupants to land-use or building area data (Jones, et al., 1986) are usually available. This is not as difficult an inventory task or as prone to error as the listing of buildings according to construction classes.

Another aspect of occupancy or use that must be collected for some studies is the type of occupancy or function of the building. For estimating the ability of emergency response agencies to experience an earthquake and yet be able to provide essential services, most loss studies pay particular attention to hospitals. In terms of the overall medical system in the area, the medical roles of other facilities, including ambulance garages, wholesale pharmaceutical supply locations, and blood banks, must also be properly inventoried. For estimating economic losses, an estimate of the economic activity occurring in buildings must be made.

The designation of type of use for facilities with essential emergency response functions (e.g., fire stations and hospitals) is almost always easily available from government agencies or other sources. Since these more essential facilities can be listed quickly, it is possible to segregate them and address their inventory and analysis tasks differently. Detailed, facility-specific techniques are more costly, but relatively few essential facilities exist (and in some cases only the most essential among this small population need detailed attention). The greater cost is also justifiable on the grounds that the vulnerability analyses for these buildings should be more accurate because these facilities are more important for emergency planning and to some extent for hazard reduction purposes.

In California, for example, there are (in about 1985) 520 hospitals, 433 essential communications facilities or emergency operating centers, and 441 police or sheriff stations (Office of Emergency Services, 1986). There is a greater number of fire stations (3,155), but many of these are small in size or significance and are generally one of the easiest of the essential emergency function buildings to field survey. In the seismic safety study for the general plan of the cities of El Cerrito, Richmond, and San Pablo in the San Francisco Bay Area (Cities of El Cerrito, Richmond, and San Pablo, 1973), every fire station in the three cities was enumerated according to address and location on a seismic hazard map, and the type of framing of walls and floor or roof was noted; this was a minor aspect of the overall project and only a small effort was devoted to it.

These different types of inventory data that relate to the construction class and the various occupancy-related information items are not centrally collected by any agency or organization, and their availability can vary from one local jurisdiction or region to the next. Skillful inventory development is largely a matter of carefully extracting the useful but inexpensive data from pre-existing sources, such as local planning or assessor's departments, or from field survey work and then moving on to a completely different source to obtain other information to fill gaps.

Facility Location

Typically seismic hazard maps of ground failure or ground shaking are only available on a relatively coarse scale. Either census tracts or zip codes often provide a more detailed scale than is required to match the detail of the seismic hazard mapping. Where detailed geologic maps showing the distribution of soft soil or high ground-water areas are not available, and where the seismic sources are relatively distant rather than located within the study area, facilities sometimes need not be located more accurately than by general district of a city, or even by city, for the purposes of that particular study.

Because refinements in the geologic data base or changes in the analysis of seismic sources may occur and because the inventory may be useful for nonseismic purposes, it is always desirable to locate facilities according to a scale at least as fine as zip codes or census tracts, unless especially rapid and inexpensive studies are to be attempted. Since Bureau of the Census data include an enumeration of one- to four-family dwellings, dwelling losses are generally estimated from an inventory that is already conveniently broken down into census tracts, block groups, and blocks.

Census tract boundaries are redrawn periodically by the Bureau of the Census, and zip codes are also rearranged by the Post Office, which create an updating problem. While not a major problem, census tract, zip code, and political jurisdiction boundaries must also be reconciled; a census tract, for example, may extend into more than one municipality.

Disaggregating the inventory down to a small geographic level is a goal sought by users, but they also face problems of confidentiality or controversy if specific facilities are identified. In the seismic safety study for San Francisco's general plan (URS/Blume and Associates, 1974), a building-specific inventory of the larger seismically hazardous or suspicious buildings of the city and county was produced, based on a rapid technique using county assessors' data and a walk-by of each major building by an experienced engineer. This detailed and potentially very useful information—the detail that users often request—was also very controversial and never made public. According to the engineer in charge of the study and the head of the planning department, the information was withheld at the direction of the city government out of fear of lawsuits. The head of the building department at that time advised in a memo that publicizing the list would do no good and would cause "panic, accusations, etc." (Finefrock, 1980).

On the other hand, failing to disclose information about hazards may increase liability exposure, so this issue of the specificity of an inventory should be considered with legal advice. It is also true that earthquake hazard inventories required by state or local law, as distinct from inventories compiled in loss estimation studies, have withstood legal tests over more than a decade.

Another approach to defining location is to use an arbitrary grid or rectangular cell system. The 1-hectare cell (about 2.5 acres) system used by ABAG in a recent earthquake loss inventory project was found to be generally adequate. In Japan, a grid is often used to map both seismic hazards and building inventories using similar small-scale cells.

Where local government assessors' files contain construction-related or other useful information, the assessor's parcel can be used as the basic mapping unit. Assessor's parcels conform to land ownership patterns, which are usually much finer-scaled in urban areas than zip codes or census tracts, or even census blocks. Census tract, zip code, arbitrary grid, and assessor's parcel boundaries are unrelated to each other, although with extra cost they can be cross-referenced.

Geographic information systems using digitized maps provide several advantages once their initial cost is paid and funding for their maintenance is assured. Changes in seismic hazard zones or contours can be easily accommodated. Changes in the facility inventory, once the new information is collected, can be included inexpensively in new calculations of loss. In addition, the mathematical manipulation of units within geographic areas (such as calculating the number of dwellings located where the intensity is estimated at a certain level) can be easily accommodated. A recent conference devoted to geographic information systems indicates the range of possible natural hazard as well as other applications (American Society for Photogrammetry and Remote Sensing, 1987).

Another great advantage of computerized approaches is in dealing with problems where various combinations of layers of information on the map must be compared. A study of regional southern California earthquake response issues (Haney, in progress) is digitizing pre-existing information, some of which is related to lifelines, from a California Division of Mines and Geology (CDMG) report (Davis et al., 1982a). Broadcast coverage areas for Emergency Broadcast System stations can be compared with the CDMG study's projection of intensities and with the languages of residents as determined from census data, for example. No files on building structures are being added to the data base, although there are plans to use the ATC-13 method in its present form for this purpose.

Two disadvantages of computerized systems are the initial costs of establishing the system and the costs of maintaining the system. The first-year cost of establishing a Regional Information Management System in southern California using the earthquake loss estimation method applied to a pilot project area in San Bernardino County was estimated at about $1 million (Schulz et al., 1983), although other nonseismic benefits were postulated.

The work in southern California that is jointly funded by FEMA and the state of California (Haney, in progress) and three recent projects illustrate this evolving approach: digitizing of several different types of seismic hazard and facility data for Sugar House quadrangle in Utah by the USGS Rocky Mountain Mapping Center (Alexander, 1987); digitizing of seismic hazard maps for San Mateo County, California (Brabb, 1985); and digitizing of a small study area in San Bernardino County, California (Schulz et al., 1983). None of these projects deal very specifically with the problem of enumerating buildings in terms of construction characteristics, which is by far the single biggest inventory problem in the earthquake loss estimation field. This is not what computerized approaches do best. Manipulation of already collected information, rather than data collection, is the strong point of the computer-aided inventory approach.

Portions of the USGS map system for the United States, the familiar topography maps produced at scales as fine as 1:24,000, are now digitized and the remainder of the USGS maps will eventually be converted to this format, allowing for various types of digitized data to be related directly without having to convert via paper maps. The U.S. Bureau of the Census will digitize the results of the 1990 census (Marx, 1986); future earthquake loss studies that tie into a geocoded information system may benefit more than at present. Many local organizations, such as utility companies, planning departments, emergency services departments, and others are investigating the potential of combining resources to produce multipurpose maps.

SUGGESTED SOURCES OF INVENTORY INFORMATION

Guidelines are suggested here for preparing rapidly an inventory of facilities when the preferred ideal inventory cannot be done for an earthquake loss estimation study. A number of ways have been used or proposed. These have typically been uniquely tailored for a particular type of loss study in a particular area. The techniques suggested or followed in preparing such inventories have been shaped not only by the kinds of data needed for the particular study, but also by the kinds of information readily available in the particular area. An additional element of expert judgment from persons familiar with the study locality has been an important part of these inventory techniques, because it typically has been necessary to infer needed end-form data from other types of information.

Inventories that are less than the ideal type have advantages as well as limitations that must be recognized in the beginning. Foremost among the advantages are: in general, they are less costly to prepare, and they typically can be completed in less time than an ideal inventory would take.

Foremost among the disadvantages are: more sophisticated expert knowledge must be employed in extrapolating essential data from available raw data, and they are less accurate than more detailed inventories and these inaccuracies carry over to the loss estimates. Poor-quality input information leads to poor output results. Rarely have earthquake loss estimation studies quantified their uncertainties, so a study with less accurate inventory, and thus less accurate loss estimates, may appear to be as valid as a more accurate study, but this is not the case.

Owing to the diverse types and forms of readily available data about facilities in a study area, a step-by-step procedure cannot be suggested for preparing an inventory, nor can it be suggested that one source of data is better than another. The process to be followed depends on several factors, among them:

- Financial resources available for the study;
- Type of loss study, which establishes the type of end-data needed for the inventory and which relates to the geographic scale, kinds of facilities and losses, and time frame as discussed earlier; and
- Kinds of existing data (i.e., what kinds of data have been compiled on, for example, schools, dwellings, publicly owned buildings, and high-rise buildings).

From earthquake loss estimate studies prepared by others and from examination of basic elements of loss estimation methods, some general guidelines for an inventory procedure can be inferred. First, the end-form of the inventory data for the particular loss study must be established, which in most cases consists of:

- Numbers of facilities of various types that are located in specified zones (e.g., blocks and census tracts), in short, a count of facilities.
- Classification of facilities according to the classes in the motion-damage relationships to be used in the analysis phase.
- Value of facilities, normalized to some base year.
- Occupancy information, since casualty loss estimates are included in many studies.
- Function or use classification, if economic sector loss estimates are to be prepared and if essential emergency response facilities are to be identified.

Second, the inventory must be built at least partly from existing data sources. Inventories created from field observation are much more costly than those based on reuse of existing data. Moreover, some of the end-form data can be extrapolated with reasonable accuracy from existing data sources, especially when someone knowledgeable about the study area is utilized. The degree of extrapolation that is acceptable is a significant issue in this regard and relates to the required overall accuracy of the result from the user's viewpoint.

Following is a brief list, with some discussion of the existing data sources most often used for preparing earthquake loss estimation inventories.

1. For housing:
   - U.S. census information. These data, giving dwelling unit counts, occupancy numbers, and relatively precise locations, are

especially useful for rapid inventories of housing, but unfortunately not of help in dealing with the other kinds of structures that often have a greater bearing on total losses (which is important from a hazard reduction viewpoint) or need for emergency response (which is important for emergency planning purposes).

- Land-use maps. Most local governments retain reasonably current maps that indicate the general land-use patterns in a community from which one can infer, although somewhat imprecisely, the general types of facilities in each zone or area.

2. For selected types of facilities, for example, schools, publicly owned buildings, hospitals, university buildings, and state-owned buildings, the following may be useful:

- Some state or local regulatory or management offices, for example, school district or public health agencies, usually retain an inventory of facilities under their jurisdiction. Sometimes these inventories have enough detail on each facility to allow direct recording of end-form data for loss estimation studies.

3. For commercial/industrial facilities:

- This is the most difficult part of any facility inventory. Unfortunately, most communities do not have data on these types of facilities that fulfill the construction data needs of an earthquake loss study inventory. Whatever information one finds for these types of facilities normally is in economic terms, for example, retail or industrial space in an area, employment by type of business, and sales volume. Assessors' records generally do not adequately define construction class, but should be checked. Insurance data that may adequately define the construction class of commercial and industrial facilities are usually proprietary. Sanborn (insurance industry) maps, if they are available for the area and are reasonably up-to-date, should be consulted.

4. For facility property value:

- Local county assessor records. Use of these records can be a tedious and time-consuming effort, depending on the way in which they are kept. Also, since values estimated for property tax assessment purposes may be artificially related to actual market or replacement property values, adjustments may be required.

5. For facility floor area:

- Local county assessor records. Building area in square feet often is included in records kept by the assessor.
- Local building department. Some building departments

retain floor area data on all facilities for which building permits have been issued.

- Local chamber of commerce, real estate, or economic development organizations. These offices often compile information on retail, commercial office, and industrial space in an area as one of the tools for promoting economic development.

6. For degree of earthquake resistance incorporated into structures of various vintages:

- Local building department and design professionals can usually provide information about the code basis of designs according to year of construction. Year of construction is a datum available for housing from the census and typically is listed in assessors' files. Sanborn maps may also be useful to identify vintages.

7. For nonbuilding facilities, for example, utilities, transportation facilities, large industries, and refineries:

- The best (and possibly only) source of information on these types of facilities is the particular industry group, regulatory agency, or owner who usually retains a detailed record of these facilities, their locations, and at least some of their construction characteristics.

The methods and sources for inventory information, whether for an ideal inventory or for one assembled less rigorously and more rapidly, are much the same. The distinguishing feature between the two in many cases is the form and degree of recordkeeping that accompanies the inventory work, which is related to cost. Accordingly, the following previously stated position can be reiterated: If an earthquake loss estimate inventory is to be compiled, it is infinitely wiser in the long run to:

- Establish a systematic form for the needed end-data;
- Compile the data in a computer-retrievable form;
- Record systematically the facility data by address or zone location; and
- Differentiate on the data record between those data that are real (correct or known) and those data that have been inferred.

POTENTIALLY HIGH-HAZARD OR ESSENTIAL FACILITIES

Potentially high-hazard facilities include large dams, nuclear power plants, and liquefied natural gas (LNG) plants. Were such a facility to be severely damaged in an earthquake the resulting loss could be very great. Assessing the likelihood of failure is much more difficult than the initial step of locating such facilities on maps and then estimating the associated exposure areas (such as the inundation area for a reservoir). The cost of a properly conducted seismic study of a single critical facility may exceed the cost of a multipurpose earthquake loss study for an entire region, and frequently quantitative loss estimates for critical facilities are beyond the scope of most large-scale loss studies. When critical facilities are excluded, this should be noted in the loss study.

Also included in this category of potentially high-hazard facilities are refineries and chemical plants, tank farms, semiconductor plants using toxic materials, laboratories, gas transmission lines, and large buildings (high rises, large plan area structures) with hundreds or thousands of occupants. It is possible within the limits of a reasonable loss study budget to inventory facilities of large potential hazard, even if the study stops short of predicting their losses or the likelihood of failures.

It is usually possible to obtain inventories of the location, size, age, and approximate construction class of essential facilities such as police and fire stations or hospitals. Because of their importance, as is the case with potentially high-hazard facilities, these essential facilities must be inventoried and field-rated on an individual basis.

Because essential emergency facilities are often individually visited, or an inventory of their construction characteristics is available from drawings or records of regulatory agencies or owners, the inventory data are more accurate than for the general population of buildings. This allows for greater accuracy in the results. As noted earlier, however, the accuracy will not be high by comparison with the accuracy available in many other fields of engineering. Even when a structural seismic analysis of an individual building is conducted, costing perhaps one-quarter to one percent of the value of the building, the results will be approximate and uncertain because of the inherent limitations in the state of the art of estimating earthquake losses.

The issues of the confidentiality or the controversial nature of facility-specific loss estimates and concern over liability are always present in this type of study. For example, the unusually detailed study of about 1,000 hospital buildings in southern California by the Office of State Architect (1982) is publicly available only in aggregate form where the identity of individual structures and their owners is concealed.

METHODS FOR EVALUATING INDIVIDUAL BUILDINGS OR FACILITIES

In many cases, the method used for facility-specific analysis is more difficult to describe in detail than the methods used for the general building stock, simply because the estimates of vulnerability are usually based on limited visits by engineers to the facilities or on reviews of drawings or other information. To simply describe the method as engineering judgment does not precisely define the method since judgments vary among different engineers. Since these facility-specific analyses will usually stop far short of a full set of calculations for loads and capacities, because of the budget limitations of large-scale loss studies, reliance on an expert's opinion is the preferred approach.

The first of the large-scale, general-purpose studies (Algermissen et al., 1972) included a rapid review of major hospitals, with the method being the judgment of one or more experienced structural engineers who were already familiar with a significant percentage of these buildings. Some field visits and quick reviews of construction drawings were used to supplement pre-existing knowledge about these buildings. Field visits are especially important for assessing the ability of an essential facility's equipment to function after an earthquake.

About 800 of the University of California's major buildings, totaling 44 million square feet, have been seismically evaluated using a rapid rating process that essentially relied on the judgment of two experienced engineers, with a construction class system derived from the ISO scheme used as a guide. Two to four days were spent to review drawings, to conduct walk-through surveys at each of the nine campuses, and to divide the buildings into four categories of vulnerability to MMI IX shaking. Then another method (McClure et al., 1979) was used, in a derivation of the ISO construction class scheme, to rate the benefit-cost ratio for each building, with the benefit being the likely savings in lives and the cost being that for strengthening.

The U.S. Navy has used a method called rapid analysis to sort buildings and spend more time analyzing the most hazardous structures. Screening proceeds from a consideration of size and functional importance of a building to a rapid calculation of loads and capacities. An application is described by Chelapati et al. (1978).

A National Bureau of Standards research effort led to the development of a technique called the field evaluation method (Culver et al., 1975). This method was not intended to evaluate essential facilities, but it is representative of rapid, building-specific rating methods. A structure's characteristics are rated according to a point system: type of vertical elements (11 classes), diaphragm rigidity (4 levels), diaphragm anchorage (4 levels), diaphragm chords (4 levels), symmetry (4 levels), quantity (4 levels), and condition (4 levels). The rating method produces an earthquake resistance point value that is then compared with values for four intensities (MMI V, VI, VII, and VIII+), with the result being a four-level (good, fair, poor, very poor) evaluation. Nonstructural components are considered via use of a few overall categories.

The inclusion of nonstructural damage in a method is unusual. The general exclusion of nonstructural damage seems to be more attributable to limited budgets rather than a disregard for the importance of this type of damage.

The field evaluation method is based on a rating of components, rather than overall engineering judgment or overall construction class. Another component-based method is the ISO (1983) *Guide for Determination of Earthquake Classifications,* which differs from the earlier ISO overall construction class method referred to as "the ISO method" throughout this paper. In the guide, which describes a point rating system, the following components are defined: framing system (16 categories) with a weighted combination for buildings where more than one framing system is present, exterior walls (12), interior partitions (3), diaphragms (7), area/height (3), ornamentation (5), configuration irregularity (4), equipment (4), design level (5), and quality control (5). The output is a point total that converts to ISO earthquake insurance guideline premium rates, rather than a direct loss estimate.

Standard and Poor's Corporation (n.d.) also uses a loss or risk estimation based on components. Local engineers are directed to tabulate a building's construction in terms of: vertical and lateral load-resisting system (27 categories), floor (21), roof (28), exterior wall (17), interior wall (13), year built, and stories.

Another building-specific, component-based rating system is the FEMA Natural Hazard Vulnerability Survey (FEMA, 1985a) method. Beginning in 1985, essential emergency response facilities began to be surveyed in different areas of the country. The earthquake, hurricane and high wind, tornado, and flood portions of the method were applied where geographically applicable according to definitions of threshold risk. The output, in addition to a specific rating of several nonstructural components (e.g., whether the generator is anchored or not), is a five-level rating. Uniform Building Code seismic zones are used, along with estimates of the building's period, mass, and other factors, to estimate the load. The construction components surveyed and numbers of classes for each are: length, width, average floor area, and height; whether designed by architect and/or engineer; year designed; frame (13 categories); shear wall type (10); total shear wall lineal footage for each axis, per story; diaphragm (7); configuration irregularities (6); connections (8); condition (3); seismic code (5); and soil (2). Geologic hazards that pertain, extracted from available published maps, are converted to a standard severity scale; hazardous appendages are noted; seven nonstructural items are rated resistant or nonresistant; and the existence or absence of an earthquake plan for the occupants of that building is noted.

A review of literature and development of a detailed component-based method intended for high-technology facilities is described in the work of EQE, Inc. (1985). A portion of this approach is derived from research on component-based earthquake loss estimation by Kustu et al. (1982). One of the advantages cited for this approach is the ability to combine the results of experimental work, which is mostly done on the scale of a component rather than a complete building, with more general approaches to loss estimation.

Where a given type of construction is of interest, such as unreinforced masonry, methods particular to this class are sometimes available. An early application of a component-rating system for purposes of rating unreinforced masonry buildings in a local government seismically hazardous building program (the first in the United States, beginning in the 1950s) was in Long Beach, California (City of Long Beach, 1977). This approach, using a concept of balanced risk, was developed by Wiggins and Moran (1971).

As noted in the discussion of lifelines, key individual lifeline structures must be evaluated with a facility-specific method. The reports by the California Division of Mines and Geology are examples of earthquake loss studies where the estimated performance of individual major bridges, highway segments, airport runways, and other specific facilities is evaluated and listed (Davis et al., 1982a,b).

PRINCIPAL ELEMENTS OF SEVERAL SPECIFIC METHODS

The NOAA-USGS Inventory Method

The NOAA-USGS method for estimating losses from earthquakes actually is a general approach that has been used in several studies undertaken over the past 15 years, usually with major roles played by S. T. Algermissen (USGS) and Karl Steinbrugge (consulting structural engineer). Its construction classes and motion-damage-loss relationships are essentially those of the ISO system and are discussed in Working Paper E. Whether or not these loss studies should be generalized and called a single method is subject to debate, but the general inventory technique is discussed here in reference to two specific applications, the San Francisco Bay Area (Algermissen et al., 1972) and the Salt Lake City Area or Wasatch Front (Rogers et al., 1976) studies.

Compared with the ATC-13 inventory method, discussed later, which attempts to enumerate every facility within the study area, the NOAA-USGS method is selective in its inventory process. In some cases, such as the Salt Lake City study, a few classes of construction, such as unreinforced masonry, can be reliably predicted to account for a large part of the total losses (Algermissen and Steinbrugge, 1984), and thus the inventory effort is more concentrated on these influential construction classes. The concept of seeking out only the "seismically suspicious" buildings (Arnold and Eisner, 1984) in an area takes this process one step further. If only major emergency response implications of a scenario are needed, one could, for example, avoid inventory of wood-frame dwellings, which are the majority of buildings in most California cities, and instead concentrate the inventory effort on downtown areas where unreinforced masonry, nonductile concrete, or other "seismically suspicious" buildings are most prevalent. (Estimating postearthquake housing problems is an emergency response task that requires dealing with all the dwelling stock.)

With respect to the inventory elements of the methods for the two studies, the Wasatch Front study is said to be the more accurate of the two because of the detailed procedures that were followed (Algermissen and Steinbrugge, 1984). This Salt Lake City study inventory procedure is summarized in that paper as follows:

> A program supervised by K.V. Steinbrugge for the U.S. Geological Survey was begun in 1974 to develop a detailed inventory of buildings by class of construction in Salt Lake City. For one to four family

> dwellings and for population distribution, the best source of data was found to be the United States Census data. The Census provides information of the numbers and geographical distribution of dwellings according to census tract. Census tracts are a convenient unit since the number of one to four family dwellings in each tract seldom exceeds 2000 units in the Salt Lake area. The most accurate cost estimates for housing were obtained from boards of realtors or realtor associations which compile frequent (usually monthly) summaries of actual dwelling sales. Aerial photos and appropriate sampling techniques were used to develop the construction characteristics of dwellings since there is a great difference in vulnerability between wood frame and other types of housing construction. Studies (Steinbrugge and others, 1969) have shown that the number of brick, concrete block and related types of construction used for dwellings in, for example, California is small (less than a few percent). It was found that brick, concrete block and related construction types made up about 60 percent of dwellings in the Salt Lake City area. A detailed inventory of buildings by classes of construction other than dwellings was undertaken by the H.C. Hugh Company of Salt Lake City for the U.S. Geological Survey. The development of the inventory was supervised by K.V. Steinbrugge. Air photos and drive-by inspection of buildings in each census tract were conducted. Construction type was noted and the dimensions of the buildings were obtained either from the air photos or from actual measurements. Replacement cost per unit area for the various classes of construction was estimated by a professional building inspector in Salt Lake City with long experience in the region. It is believed that the inventory obtained in Salt Lake City is extremely accurate for the purposes of an earthquake loss study and that the errors in the estimation of ground motion are likely to be much larger than the inventory errors in this particular study.

In contrast, the inventory method for the San Francisco Bay Area was based on building information extrapolated from census data (dwellings) and modified fire insurance property values (other buildings). Algermissen and Steinbrugge (1984) give the following description of the inventory method in this case.

> Data on dwellings was obtained in the same manner as described in the Salt Lake City study—i.e., from census data and summaries of real estate transactions. For buildings other than dwellings a novel approach was used. Quoting from Steinbrugge and others (1981): "The initial data were fire insurance property values by county for northern California and an assumed 8.3 magnitude earthquake on the San Andreas fault. These values included dwellings, commercial buildings, manufacturing plants, warehouses, offices, and all other fire-insured properties. These property values were increased to include non-insured private property as well as increased to include under-insured property. Adjustments were made on a judgement basis to include the value of Federal, State of California, and local governments-owned buildings. Intensities from the NOAA report's isoseismal maps were

converted into loss factors, or the percent loss based on an impersonal definition basis. These percentages were multiplied by the property values to obtain the total impersonal loss by county in the study area, then summed to obtain the total aggregate loss. In this process, values were adjusted to compensate for inflation to 1980.

Building contents for the aforementioned San Andreas earthquake were analyzed in a similar manner to derive the total contents aggregate loss.

A strong point of this NOAA-USGS inventory approach is its balancing of accuracy versus detail—pushing the available data as far as appropriate and then stopping short of making further assumptions that would be necessary to obtain more detailed estimates. The expertise used in these studies appears to be appropriate to the task: While earthquake engineering experts were employed, the expertise of real estate, building inspection, insurance, or other local sources of knowledge concerning the distribution of classes of construction was also utilized. A weak point in the method is that complete documentation of the technique—complete enough for others to replicate or test the technique in an updating study of the same area or to apply it elsewhere—is lacking. Since the experience of a few key individuals has been heavily relied on in these studies, documentation may be inherently difficult, and to some extent it would be more a matter of teaching an art rather than specifying the precise steps that could be mechanically followed.

The FEMA/ATC-13 Inventory Method

The method for estimating losses from earthquakes described in the ATC-13 report (Applied Technology Council, 1985) was designed to provide information on damage, casualties, and immediate functional loss to be combined with an economic model for predicting economic losses, that is, direct building and structure losses, loss of equipment, production losses, losses to infrastructures such as utilities and transportation systems, and losses due to interrupted business. To serve its original intended purpose, the inventory and loss estimates had to be compatible with the economic sectors to be used in the interindustry input-output model. Accordingly, this method is comprehensive in the inventory it seeks. Forty classes of building construction and 38 nonbuilding structure classes are defined, and each facility must also be defined in terms of one of 35 occupancies or "social functions."

The broader nature of the ATC-13 inventory makes it only partially comparable with the NOAA-USGS method, and only the portion of the ATC-13 inventory method that deals with buildings is discussed here. It should be noted that the breadth of the ATC-13 method—which encompasses lifelines, industrial structures, ground failures, and functional losses in a quantitative manner—is one of its significant accomplishments.

The FEMA/ATC-13 inventory method aims at compiling locations and quantitative measures for all facilities plus descriptors of the construction that allow classification for use in estimating damage. Facility values are also needed, as is information about each facility's economic use for input into an economic model that begins with damage and reduction in functional levels and then forecasts longer-term economic impacts. The portion of the loss study that inventories the information and analyzes it to produce estimates of immediate losses is called FEDLOSS by FEMA in its automated form. The portion of the loss study that would employ an economic input-output model to estimate longer-term economic losses is called FEIMS (FEMA Earthquake Impacts Modeling System).

The ATC-13 report states its preferred source of inventory data as pre-existing inventories of facilities containing the required construction class detail, but because even less demanding classification systems cannot be supported by data that have already been collected, this preference will in most cases be unfulfilled. This hoped for pre-existing inventory is called a Level 1 inventory. A Level 2 inventory, the one necessary in most cases, will be described below. A Level 3 inventory is simply a complete synthesis of an inventory based only on overall population data, such as by assuming both the number and construction types of all buildings in a city on the basis of its population.

In the Level 2 approach, the location and descriptors of construction are obtained by extrapolation from a variety of economic and census data. The sources for these data are discussed in ATC-13, and are described in detail in the FEMA *Data Base Catalog* (FEMA, 1985b), which lists the many different computer data files acquired by FEMA from other agencies, through marketing or economic analysis services, or in some cases from within the FEMA organization. These data bases have been accumulated and funded primarily as a function of the civil defense program of FEMA and its predecessor agencies and have been used in nuclear war loss estimations. Correlations between facility and use classification were developed in the

ATC-13 project to allow for the transformation of economic data into construction data. The relationships imputed in the ATC-13 study were developed only in the context of California.

In some ways, facility classifications of the ATC-13 method are similar to those of the USGS method, but are more detailed. The ATC-13 method has almost two times as many classes of construction as the NOAA-USGS method (40 versus 21, comparing building classes only), and each individual facility must also be assigned one of 35 use categories. There are, however, some buildings whose construction would be more precisely defined by the NOAA-USGS inventory (or ISO) scheme, such as a steel moment-resisting (rigid frame, or rigidly connected joints) building with flexible diaphragms (or floors acting to resist lateral forces).

Clearly more information is required to construct an inventory for the 40 ATC-13 classes of facilities than for 21 classes. Given any comparable inventory budget, the accuracy of the assignment of a facility to its proper class in the ATC-13 method would usually be less than in the NOAA-USGS method.

The greatest advantage of the ATC-13 method is that it is very powerful: it can assemble a very large and detailed inventory inexpensively by using already computerized socioeconomic data. This is also its biggest disadvantage compared to methods that use actual inventory data obtained from or checked by fieldwork with less extrapolation.

The large amount of extrapolation and reliance on rules of thumb developed by combining the opinions of earthquake engineering experts can be seen from a typical example of how the inventory method would operate. First, the ATC-13 method would probably start with the number of employees who work at a commercial or industrial business. (For some small number of industrial facilities, the FEMA data bases may contain construction data and thus make the Level 2 extrapolations unnecessary. The number of one- to four-family dwellings can be obtained directly from census data.) One of a few data bases, such as the Census Bureau's Manufacturing Establishments by Industry Sequence, would be used in which the known information (excluding economic data on value of goods produced, for example) is simply number of employees and the location by zip code, along with the detailed (four-digit) Standard Industrial Classification (SIC) code that defines the type of economic activity. The precision of the location is sometimes but not usually an issue. For example, the zip code location listed for a supermarket company in a city will lump all of the employees at the headquarters' zip code.

These data—number of employees, type of economic activity, and location—are the only data known directly for the facility in most cases, and the remainder of the necessary data is synthetic. As ATC-13 notes,

> The FEMA Manufacturing Establishment File, the Wholesale Trade Establishment File, and other business establishment/company files do not include either the sise, location, or structural characteristics of facilities. This information must be estimated based on economic data such as the number of employees or annual production amounts. . . . Few if any existing facility databases or the inventories synthesized using Level 2 and 3 procedures contain sufficient information to allow the accurate determination of Earthquake Engineering Facility Classifications.

The second step in the ATC-13 inventory method is to relate the number of employees to the building size, according to estimating factors for different occupancies. These relationships are generally drawn from transportation studies, especially those of Caltrans (California's highway department). In the ABAG inventory method (Perkins et al., 1986), similar relationships were used to estimate building square footage, using instead Federal Highway Administration data. This extrapolation is more accurate than those of the other steps and is not a major source of error. As noted in the work of Jones et al. (1986), stable and reliable relationships exist for square footage per person estimating factors, although a curious effect of this relationship is that an inventory would show buildings swelling and shrinking in size as fluctuations in the economy cause the number of employees in a building to rise or fall.

The third step is to divide up the buildings, known at this point only in terms of location and, by extrapolation from number of employees, the size, into construction classes. The height of the approximately 3,000 high rises in California can be known from files specific to high rises assembled by the Council on Tall Buildings of Lehigh University. For the majority of buildings that remain, they can be divided into mid-rise and low-rise categories based on rules of thumb developed by a process of asking earthquake engineering experts their opinions.

In this third step of developing a synthetic construction class distribution, the other basic task is to assign a construction class (e.g., reinforced masonry shear wall with moment-resisting frame, reinforced masonry shear wall without moment-resisting frame) to each facility. This was done by obtaining collective expert opinion from the engineers involved in the ATC-13 project, assigning a certain percentage of the buildings in each use category to each of the construction classes. In each use category (e.g., single-family dwelling) the fractions for low-rise wood frame, low-rise reinforced or unreinforced mansonry, and so on sum to 100 percent.

The result is the end-form data: construction class (and high-, mid-, or low-rise subclass designation), floor areas, use, and zip codes for all buildings in the study area. Steps one and two involve relatively noncontroversial extrapolations common to many loss estimation methods. It is the third step, where the inventory variable of central importance—construction class—is synthesized on the basis of opinion, that involves untested relationships. Essentially, the construction class inventory is synthesized knowing only the number of employees, the zip code of the business, and the economic function.

Comparison of the NOAA-USGS and FEMA/ATC-13 Inventory Methods

A full application of the ATC-13 method has not yet been reported in the literature. The NOAA-USGS method is a general method that can be extracted from the reports of its application, for example, the large-scale NOAA-USGS loss study of San Francisco. ATC-13 is a report that describes its method very specifically, but there is no loss estimation study or actual application to refer to as a concrete case. This makes a comparison of the two inventory methods difficult. Also, the two methods were devised for different purposes.

Although the comparative information given in Table D-1 on the type of end-form data implies that inventories would be much the same for both methods, this is not precisely true. Somewhat different characteristics are used for classifying the facilities in the two methods, and this affects the details for each. However, the striking difference in the two methods is not the data they seek, but how they assemble them. While both methods use judgment in the inventory process, the ATC-13 method is more reliant on judgment. The application of judgment in the ATC-13 method is, however, generally more apparent, in that it would be easier for other investigators to rely on the published description of the method, reuse it, and replicate the results obtained by others.

Descriptors used in the classification process for each method

TABLE D-1 Comparison of ATC-13 and NOAA-USGS Inventory Data

FEMA/ATC-13	NOAA-USGS
Seventeen basic building construction classes with subclasses for low, mid-, or high-rise heights, and combinations of systems (such as shear wall and frame); 40 classes total	Nine basic building construction classes, with subclasses for size and degree of earthquake-resistant design; 21 classes total
Primary categories	Primary categories
Wood frame	Wood frame
Light metal	Light metal
Unreinforced masonry	Unreinforced masonry
Reinforced-concrete shear wall	Reinforced-concrete shear wall
Reinforced-masonry shear wall	Reinforced-masonry shear wall
Braced steel frame	Steel frame
Moment-resisting steel frame	Concrete frame
Moment-resisting concrete frame	Precast concrete
Precast concrete	Tilt-up
Long span	
Tilt-up	
Mobile home	
Descriptors[a]	Descriptors[a]
Structural material	Structural material
Framing system	Framing system
Floor area	Floor area
Height	Height
Ductility	Earthquake-resistant design
Economic use, social function	Economic use, social function
Thirty-five classes that are cross-referenced to the broader range of SIC classes; each facility inventoried is assigned a class	Collected for some essential facilities (e.g., hospitals) but not collected for each building

[a] All of these descriptors are not necessarily inventoried for all classes.

vary in detail in some cases but would be identical for the two methods in other cases, for example, construction material or height. The lists shown in Table D-1 are in a different form than they appear in either method and are organized more generically to allow for comparisons. For example, the NOAA-USGS approach contains a class for mixed construction (different wall and diaphragm material) that includes buildings with wood roof and floors with walls of tilt-up, reinforced masonry (brick or block) or poured-in-place, reinforced-concrete construction. Variations in earthquake-resistant quality ratings can result in these buildings then being assigned to different classes (Insurance Services Office, 1977). In Table D-1, these variations on the mixed NOAA-USGS class of construction are listed as separate classes to allow for closer comparison with ATC-13.

Inventories for the two methods contain much of the same type of information, although the broader purpose of the ATC-13 method (economic loss estimation) leads it to develop two additional detailed sets of information, one on economic function and the other on lifelines and nonbuilding structures.

The PEPPER Study Inventory Method

The method for estimating earthquake losses used in the PEPPER (Pre-Earthquake Planning for Post-Earthquake Rebuilding) study (Spangle, 1984) relied on automated data already collected by the planning department of the City of Los Angeles. No new field surveys were conducted, partly because of budget limitations and partly to try to test the usefulness of this large data base, which had been assembled from assessors' tax records and other sources. As partial checks on the accuracy of this comprehensive data base of about 1 million buildings, files containing information specific to building construction characteristics were consulted. An accurate inventory of pre-1934 (preseismic code) unreinforced masonry buildings was already in existence because of the city's retroactive seismic ordinance, and the characteristics of high-rise buildings were tabulated in a real estate survey. Census data on population and housing from the 1980 census were used, along with a 1974 city study.

Buildings were (1) aggregated in planning areas of the city, and (2) classified according to type of construction in five classes: steel, concrete, masonry, wood, and special. Use was classified according to four classes: residential (with three subclasses), commercial, industrial, and other. No other details appear in the report to suggest the way in which buildings were allocated to each class. As noted in the study's engineering report, "The inventory of structures . . . is probably the least reliable component of the various factors that determine the damage pattern" (Degenkolb, 1984).

The building classification method might be described as an adjusted NOAA-USGS method. The PEPPER method adjusted the basic ISO or NOAA-USGS construction classification system because the available data were not that finely subdivided. This also had implications for the analysis task, because the hybrid or combined construction classes of the PEPPER inventory had to be analyzed using hybrid motion-damage relationships. The beginning form of the data in the city planning department's data base did not differentiate high rises according to their type of enclosure system (e.g., curtain wall, poured-in-place concrete). Inferences based on year of construction (e.g., assuming that post-1960 high rises were predominantly of curtain wall exterior) were used.

One point made by this study is that even if a very large computerized file of buildings exists, this does not necessarily mean that the data are detailed or accurate. Lack of detail is evident from the fact that all steel buildings, or all concrete buildings, for example, were lumped together in one class. This level of detail is a common constraint in the use of assessors' or local planning department data. The accuracy of the inventory was also limited and was related to the fact that this data base was assembled for nonseismic, nonengineering purposes. An example of a major type of inaccuracy concealed in the data base was that high-rise buildings were sometimes described as having wood-frame structures. Another problem was that this data base was not current because the cost of updating it had been considered too high by the planning department a few years after it had been created.

POSTEARTHQUAKE STUDIES OF LOSS

Related to the pre-earthquake inventory problem is the task of postearthquake inventory of damage by class of construction, location, ground conditions, and intensity or measured ground motion. Although all loss estimation investigators bemoan the fact that there are not more historical loss data available, there are few ongoing efforts outside of the insurance industry to collect this type of data after earthquakes occur. As pointed out in the Earthquake Engineering Research Institute's guide to postearthquake investigation (Earthquake Engineering Research Institute, 1977), undamaged as well as damaged buildings should be tabulated. Statistical techniques provide many tools for analyzing damage data, and these are explained in the guide in a special section. However, most earthquake reconnaissance reports or detailed studies do not comprehensively report damage or loss data, but rather concentrate on the more unique or instructive individual cases of damage.

Because the types of pre-earthquake inventory data and construction classes that are generally used are known prior to initiating postearthquake investigations, damage data could be collected efficiently, on a sampling basis where necessary, to try to fill gaps in historical loss data. Although in theory systematic studies of building damage could result in complete data for estimating purposes, in practice this is not so. Construction innovation will always be ahead of recorded earthquake experience. Earthquakes in Chile and Mexico in 1985 tested the building construction methods in use in these countries of the 1950s, 1960s, and 1970s. There are no data, however, on the performance, under moderate to severe ground motion, of tall welded perimeter tube structures, modern mid-rise steel-braced frame structures, or large two-story tilt-up concrete structures that are common in many parts of the United States.

SUMMARY

In theory, a perfect inventory can be created. However, it will never be achieved because of cost and time constraints. Therefore, ways of obtaining the most useful, imperfect inventory are being studied. The attempt to start from an economically based inventory, as in ATC-13, is not advised. Although the final output is intended to be economic, economic loss can only be estimated on the basis of an estimate of earthquake damage. Earthquake damage can only be estimated accurately when building construction data are directly sought. Converting economic data into construction classification data is not recommended because this can greatly reduce the accuracy of the inventory.

If the focus is to be on building damage, then the inventory should focus on vulnerable or "seismically suspicious" buildings. Procedures that provide an initial screening by low-cost means, leading to a more detailed survey to provide accuracy, make more sense than an attempt to develop a complete inventory from which the hazardous buildings must be selected.

Facilities with a potential for large loss, or with essential emergency functions, should be inventoried on a case-by-case, field survey basis.

The insurance industry, particularly in California, has much information both on building damage and on building inventory. This information is generally unobtainable due to industry's confidentiality requirements and competitiveness, although the California

Department of Insurance obtains this information, aggregated by geographic zone and class of construction, on an annual basis. Obtaining some of this information would benefit national or regional interests, solve some of the data problems of earthquake damage estimating, and yet preserve such proprietary information as the industry deems necessary.

Working Paper E
Relationships of Ground Motion, Damage, and Loss

Although in actual practice the steps in a loss estimation study do not necessarily proceed sequentially, the previously discussed tasks of seismic hazard analysis (Working Paper C) and inventory (Working Paper D) are conceptually the two steps that precede the process of relating the ground motion or ground failure to a given construction class to estimate damage. This paper also discusses relating damage to property loss, casualties, or functional loss. The discussion here is limited to the effects of ground shaking on buildings and lifelines; the effects of ground failures are treated in Working Paper G.

Material presented in the two earlier working papers is directly applicable here. Working Paper C discussed the limitations of the Modified Mercalli Intensity (MMI) scale and other problems in the accurate definition of the ground motion to which the inventory should be subjected in the motion-damage analysis step. Working Paper D explained that the construction classification system is a part of both the inventory process and the motion-damage analysis step because the inventory information must be collected with the same construction classes used in relating the seismic hazard to construction classes through motion-damage relationships.

Many methods of relating ground motion, or less commonly ground failures, to damage have been proposed or developed. However, in the context of large-scale, general-purpose loss estimation studies the number of basic approaches is relatively small. In this paper, three particular methods are discussed because they bring out different aspects of the possible ways to approach this problem of relating motion, damage, and loss.

The loss estimation method referred to here and elsewhere in this report as the NOAA-USGS method is also, in terms of the motion-damage analysis step, essentially the Insurance Services Office (ISO) method. As explained earlier, this method was used in the first large-scale studies produced by the National Oceanic and Atmospheric Administration (NOAA) and later, with essentially the same personnel, by the U.S. Geological Survey (USGS) when NOAA's earthquake loss estimation functions were shifted to USGS.

This method has been molded by the work of Algermissen, Steinbrugge, and others. The studies of San Francisco (Algermissen et al., 1972), Los Angeles (Algermissen et al., 1973), Puget Sound (Hopper et al., 1975), and Salt Lake City (Rogers et al., 1976) are examples of the use of this method. It is the method that has been applied in most of the urban- or regional-scale studies of the type focused on in this report (studies intended for disaster planning and hazard reduction purposes).

It is also the method that has been most widely used in the property insurance industry. The NOAA-USGS or ISO method produces damage estimates in the form of mean damage ratios for each construction class—percentages associated with each MMI level indicating the average property loss in terms of cost of repair or replacement divided by replacement cost. In the NOAA-USGS method, lifelines and nonbuilding structures are analyzed by different methods than the mean damage approach applied to buildings.

The ATC-13/FEMA approach was produced by the Applied Technology Council and funded by FEMA (Applied Technology Council, 1985). While it has yet to be carried out in a loss study resulting in a published report of the type produced for several regions of the country by the NOAA-USGS method, it is a recent, comprehensive effort that involved many experts and it surveyed and evaluated a broad range of analysis methods and data.

The ATC-13 method uses the format of the damage probability matrix to present its damage estimates for each MMI level: the percentage of facilities that would fall into each of seven damage levels is given for each construction class (with these damage levels described verbally, with property damage ratio ranges, and with central damage ratios). For each MMI, the distribution of damage for a construction class can also be converted into an overall damage ratio. In the ATC-13 method, lifelines and nonbuilding structures are essentially handled with damage probability matrices the same way as for buildings.

A third basic method to be discussed is the application of fragility curves to the task of estimating regional-scale earthquake losses. The Central U.S.-Six Cities study (Allen and Hoshall et al., 1985) used this approach. The motion-damage portion of this study's method, the development of fragility curves based on a combination of empirical or historical data and theoretical calculations, was developed by Jack Benjamin and Associates, Inc. (Kircher and McCann, 1984) and is occasionally referred to as the JBA method later. One fragility curve describes the probability a given construction class will reach or exceed one particular level of damage at various intensities of shaking. A set of curves, to cover all the damage states, is used for each construction class. Fragility curves and damage probability matrices are similar in the information they provide and one can be converted into the other. Fragility curves present the information graphically, while damage probability matrices present the information in tabular form. In the JBA-Central U.S. study's method, lifelines and nonbuilding structures were treated with fragility curves in a manner parallel to that used for buildings.

NOAA-USGS MOTION-DAMAGE RELATIONSHIPS

The earliest U.S. attempt at estimating earthquake property loss on a large scale began in 1925 when engineers Harold Engle and Jack Shields gathered data on the damage caused by the Santa Barbara earthquake for use by the insurance industry. This work has continued and has resulted, after several developments and refinements, into the NOAA-USGS method or the similar ISO method.

The generic NOAA-USGS motion-damage relationship is shown in Figure E-1. The truncation of the mean damage ratio curve at MMI IX-X is due to the fact that intensities above this point have sometimes been assigned to sites in previous earthquakes on the basis of ground failure, not ground shaking. Table E-1 briefly tabulates the construction classes. Each class is described with approximately a paragraph in the *Commercial Earthquake Insurance Manual* (ISO, 1977).

The damage ratio is the percentage damage related to cost of

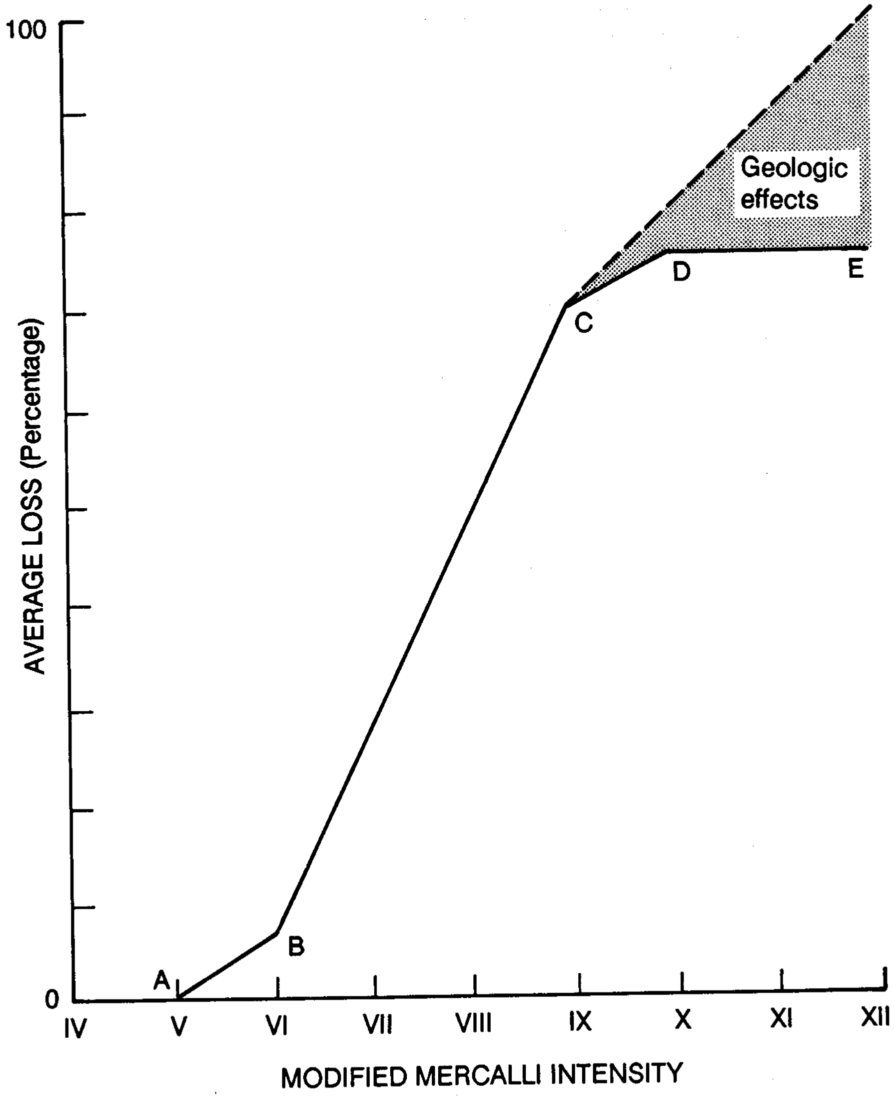

FIGURE E-1 Relationship of ground failures to ground shaking in the Modified Mercalli Intensity scale. Source: Steinbrugge (1982).

replacement. Mean damage ratios are used because they are average factors for all buildings of given classes. They do not give the distribution of damage, such as how many buildings had little or no damage or how many had moderate damage. The mean damage

TABLE E-1 Construction Classes Used in the ISO and NOAA/USGS Methods

Building Class	Brief Description of Building Subclasses
1A-1	Wood-frame and stuccoed frame dwellings regardless of area and height
1A-2	Wood-frame and stuccoed frame buildings, other than dwellings not exceeding three stories in height or 3,000 square feet in ground floor area
1A-3	Wood-frame and stuccoed frame structures not exceeding three stories in height regardless of area
1B	Wood-frame and stuccoed frame buildings not qualifying under class 1A
2A	One-story, all metal; floor area less than 20,000 square feet
2B	All metal buildings not under 2A
3A	Steel frame, superior damage control features
3B	Steel frame, ordinary damage control features
3C	Steel frame, intermediate damage control features (between 3A and 3B)
3D	Steel frame, floors and roofs not concrete
4A	Reinforced concrete, superior damage control features
4B	Reinforced concrete, ordinary damage control features
4C	Reinforced concrete, intermediate damage control features (between 4A and 4B)
4D	Reinforced concrete, precast reinforced concrete, lift slab
4E	Reinforced concrete, floors and roofs not concrete
5A	Mixed construction, small buildings and dwellings
5B	Mixed construction, superior damage control features
5C	Mixed construction, ordinary damage control features
5D	Mixed construction, intermediate damage control features
5E	Mixed construction, unreinforced masonry
6	Buildings specifically designed to be earthquake resistant

SOURCE: Algermissen and Steinbrugge, (1984). For more complete descriptions of each class, see Iso (1977) and McClure et al. (1979).

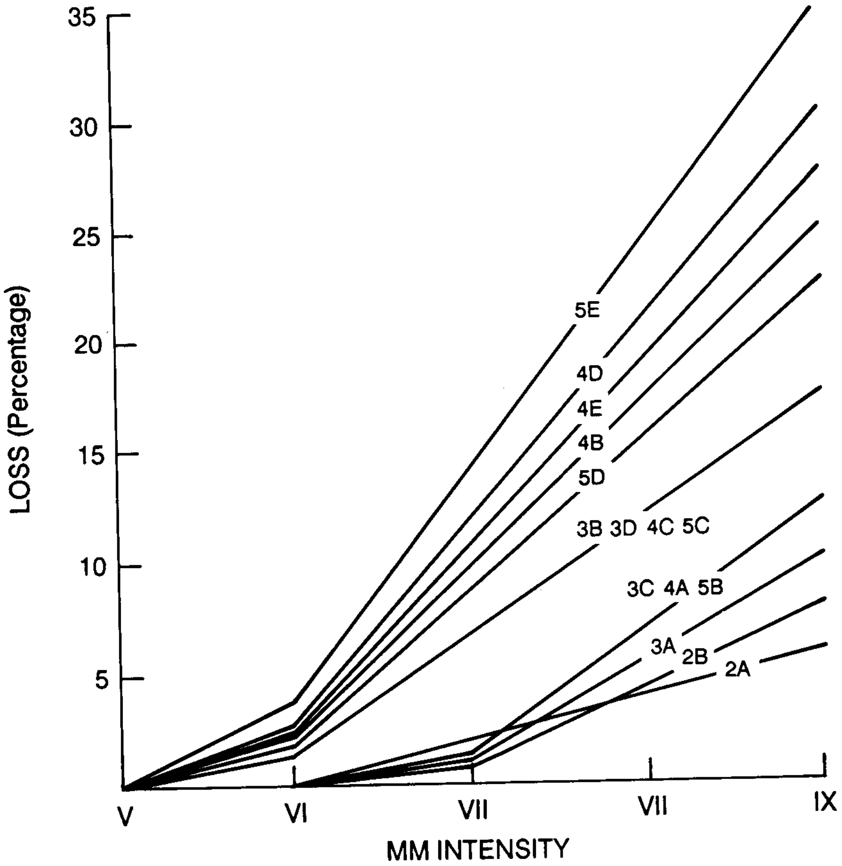

FIGURE E-2 Mean damage ratio curves used in the NOAA-USGS method. Source: Algermissen and Steinbrugge (1984).

ratio directly defines property loss, but does not directly indicate loss of function or number of casualties. Figure E-2 shows some of the mean damage ratio curves used in the NOAA-USGS method.

The amount of historic damage data available on some of the classes of construction, particularly wood-frame dwellings, is extensive, whereas more judgment and fewer data are employed to develop damage ratios for high-rise buildings or many low-rise commercial-industrial construction classes for which there is less experience. The ISO system generally limits itself to classes of construction for which there are historic data.

Single-family wood-frame dwellings are the class of construction having the greatest historical data, with the possible exception of mobile homes. The accuracy of the basic NOAA-USGS method for this class is high as judged by the work of McClure (1967),* whose property loss relationships (based on the 1952 Kern County earthquakes) predicted a total loss of $3.8 million when applied to the 1969 Santa Rosa earthquakes, whereas the actual postearthquake estimated dwelling loss figure was $4 million (Steinbrugge et al., 1970).

Another test of a loss estimation method for single-family dwellings is provided in Rinehart et al. (1976) wherein the results of a modified version of the 1969 method by Steinbrugge and others are favorably compared with data from the 1971 San Fernando earthquake. The 1971 data on all of the approximately 12,000 dwellings in one area of the San Fernando Valley where the shaking was strongest are unusually large and detailed. Often only rough or semiquantitative data on a few dozen buildings of one construction class are available from an earthquake, or the reports are selective (typically only noting cases of dramatic damage).

ATC-13 MOTION-DAMAGE RELATIONSHIPS

The ATC-13 method does not describe its building construction classes in as much detail as in the NOAA-USGS scheme, but includes many structures that are not addressed in the NOAA-USGS method. It has a total of 78 classes of structures, 40 of which are buildings and 38 of which are lifeline-related or equipment classes. These classes are listed in Table E-2.

Lacking the major source of hard data in the ISO or NOAA-USGS method, which was proprietary to the insurance industry, ATC-13 relied on the expert opinion of experienced individuals in the earthquake engineering field to produce motion-damage relationships. The techniques used for processing the questionnaire answers are described in the ATC-13 report.

The form in which the ATC-13 motion-damage relationship for each class was solicited from the experts, and the way in which the combined or consensus expert opinion was presented, was the damage probability matrix. This format and idea was originated by Martel (1964) and independently developed in the Massachusetts Institute

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*Given the loose definition of "NOAA-USGS" method used here, the McClure work fits this definition.

TABLE E-2 Earthquake Engineering Facility Classification

Facility	Classification Number
BUILDINGS	
Wood frame (low rise)	1
Light metal (low rise)	2
Unreinforced masonry (bearing wall)	
Low rise (1-3 stories)	75
Medium rise (4-7 stories)	76
Unreinforced masonry (with load-bearing frame)	
Low rise	78
Medium rise	79
High rise (> 8 stories)	80
Reinforced concrete shear wall (with moment-resisting frame)	
Low rise	3
Medium rise	4
High rise	5
Reinforced concrete shear wall (without moment-resisting frame)	
Low rise	6
Medium rise	7
High rise	8
Reinforced masonry shear wall (without moment-resisting frame)	
Low rise	9
Medium rise	10
High rise	11
Reinforced masonry shear wall (with moment-resisting frame)	
Low rise	84
Medium rise	85
High rise	86
Braced steel frame	
Low rise	12
Medium rise	13
High rise	14
Moment-resisting steel frame (perimeter frame)	
Low rise	15
Medium rise	16
High rise	17
Moment-resisting steel frame (distributed frame)	
Low rise	72
Medium rise	73
High rise	74
Moment-resisting ductile concrete frame (distributed frame)	
Low rise	18
Medium rise	19
High rise	20

TABLE E-2 (Continued)

Facility	Classification Number
Moment-resisting nonductile concrete frame (distributed frame)	
Low rise	87
Medium rise	88
High rise	89
Precast concrete (other than tilt-up)	
Low rise	81
Medium rise	82
High rise	83
Long -span (low rise)	91
Tilt-up (low rise)	21
Mobile homes	23
BRIDGES	
Conventional (less than 500-ft spans)	
Multiple simple spans	24
Continuous/monolithic (includes single-span bridges)	25
Major (greater than 500-ft spans)	30
PIPELINES	
Underground	31
At grade	32
DAMS	
Concrete	35
Earthfill and rockfill	36
TUNNELS	
Alluvium	38
Rock	39
Cut and cover	40
STORAGE TANKS	
Underground	
Liquid	41
Solid	42
On ground	
Liquid	43
Solid	44
Elevated	
Liquid	45
Solid	46

TABLE E-2 (Continued)

Facility	Classification Number
ROADWAYS AND PAVEMENTS	
Railroad	47
Highways	48
Runways	49
CHIMNEYS (high industrial)	
Masonry	50
Concrete	51
Steel	52
CRANES	53
CONVEYOR SYSTEMS	54
TOWERS	
Electrical transmission lines	
Convention (less than 100-ft high)	55
Major (more than 100-ft high)	56
Broadcast	57
Observation	58
Offshore	59
OTHER STRUCTURES	
Canal	61
Earth-retaining structures (over 20-ft high)	62
Waterfront structures	63
EQUIPMENT	
Residential	64
Office (e.g., furniture, computers)	65
Electrical	66
Mechanical	68
High technology and laboratory	70
Trains, trucks, airplanes, and other vehicles	90

SOURCE: Applied Technology Council (1985).

TABLE E-3 General Form of Damage Probability Matrix as Used in ATC-13 (in percent)

State	Damage Factor Range	Central Damage Factor	Probability of Damage by MMI[a]						
			VI	VII	VIII	IX	X	XI	XII
1--None	0	0.0	95.0	49.0	30	14	3	1	0.4
2--Slight	0-1	0.5	3.0	38.0	40	30	10	3	0.6
3--Light	1-10	5.0	1.5	8.0	16	24	30	10	1.0
4--Moderate	10-30	20.0	0.4	2.0	8	16	26	30	3.0
5--Heavy	30-60	45.0	0.1	1.5	3	10	18	30	18
6--Major	60-100	80.0	--	1.0	2	4	10	1	39
7--Destroyed	100	100.0	--	0.5	1	1	3	8	38

[a] Example values are listed.

NOTE: These definitions are used as a guideline:

1--None: no damage.
2--Slight: limited localized minor damage not requiring repair.
3--Light: significant localized damage of some components generally not requiring repair.
4--Moderate: significant localized damage of many components warranting repair.
5--Heavy: extensive damage requiring major repairs.
6--Major: major widespread damage that may result in the facility being razed.
7--Destroyed: total destruction of the majority of the facility.

SOURCE: Applied Technology Council (1985).

of Technology Seismic Design Decision Analysis research program by Whitman et al. (1973).

Table E-3 shows a generic ATC-13 damage probability matrix. MMI XI and XII are used here to refer to increasingly severe ground motion, beyond the IX–X point; this is not a literal interpretation of the scale's reference to ground failure indicators at these highest two intensities. Examples of damage probability matrices produced by expert opinion in the ATC-13 project are shown in Table E-4. Facility class 73 (medium-rise moment-resisting distributed steel frame) and 74 (same, except high rise) are very earthquake resistant. Classes 75 and 76 are low-rise and medium-rise, unreinforced-masonry bearing walls, which are very damageable. At any given intensity, the distribution for the steel frames will be seen to be concentrated at a much lower level of damage than for the unreinforced masonry. In any column, the percentages total to 100.

Although these expert opinion matrices show that for any intensity the buildings are usually contained within two or three damage levels, this is not quite consistent with observations of actual

TABLE E-4 Damage Probability Matrices From ATC-13

Central Damage Factor	Modified Mercalli Intensity						
	VI	VII	VIII	IX	X	XI	XII
			Facility Class = 73				
0.00	22.4	1.1	***	***	***	***	***
0.50	51.3	34.0	2.5	***	***	***	***
5.00	26.3	64.9	95.4	83.1	29.5	9.2	0.2
20.00	***	***	2.1	16.9	70.5	80.7	50.6
45.00	***	***	***	***	***	10.1	49.2
80.00	***	***	***	***	***	***	***
100.00	***	***	***	***	***	***	***
			Facility Class = 74				
0.00	26.8	0.5	***	***	***	***	***
0.50	60.0	22.2	2.7	***	***	***	***
5.00	13.2	77.1	92.3	58.8	14.7	5.9	0.8
20.00	***	0.2	5.0	41.2	83.0	67.1	42.3
45.00	***	***	***	***	2.3	26.9	55.7
80.00	***	***	***	***	***	0.1	1.2
100.00	***	***	***	***	***	***	***
			Facility Class = 75				
0.00	***	***	***	***	***	***	***
0.50	9.1	0.6	***	***	***	***	***
5.00	90.5	55.5	10.9	0.5	***	***	***
20.00	0.4	43.4	66.0	22.4	2.0	0.1	0.1
45.00	***	0.5	22.9	65.9	35.0	10.1	3.4
80.00	***	***	0.2	11.2	62.5	83.1	50.4
100.00	***	***	***	***	0.5	6.7	46.1
			Facility Class = 76				
0.00	***	***	***	***	***	***	***
0.50	4.7	1.5	***	***	***	***	***
5.00	89.9	49.5	3.7	***	***	***	***
20.00	5.4	46.4	53.3	7.6	0.9	***	***
45.00	***	2.6	42.0	63.4	21.4	5.3	3.1
80.00	***	***	1.0	29.0	74.7	80.0	43.0
100.00	***	***	***	***	3.0	14.7	53.9

***Very small probability.

SOURCE: Applied Technology Council (1985).

earthquake performance. For example, at MMI VIII or IX, no unreinforced-masonry buildings are predicted to collapse, whereas in areas assigned those intensities in the 1933 Long Beach or 1983 Coalinga earthquakes, collapses of this class of construction did occur—5 percent in 1933 in Long Beach (Wailes and Horner, 1933) and 30 percent in Coalinga in 1983 (Reitherman et al., 1984).

It has been suggested that in the ATC-FEMA method, a larger spread of damage classifications could be attained for any intensity of shaking by averaging the proportions of each central damage factor one or two steps down and one or two steps above the desired MMI intensity. (The matrices apply to "average California" construction.)

For some purposes, the average damage ratio (called damage factor in the ATC-FEMA method) is not sufficient; instead a matrix of the distribution of the degree of damage, as provided by the ATC-FEMA method, is needed. This would be important when considering effects of deductibles for earthquake insurance, or calculating the number of homeless, casualties, and so on. Another recent study used a different method for the expression of damage. The Central U.S.-Six Cities study (Allen and Hoshall et al., 1985) presented the relationship of motion to damage in terms of fragility curves. This adaptation of fragility curves to the task of large-scale loss estimation is described in Kircher and McCann (1984).

"Fragility curves . . . provide essentially the same information as does a DPM (damage probability matrix), but in graphical rather than tabular form" (Whitman, 1986). Figure E-3 describes the dameageability or fragility of one class of construction. In this case, it is a general class of "all wood-frame buildings" which would be applicable where distinctions between above and below standard wood-frame buildings cannot be made. Figure E-3 illustrates that for earthquake intensity MMI IX, there is a:

- 0.95 probability of at least nonstructural damage,
- 0.91 probability of at least slight structural damage,
- 0.23 probability of at least moderate structural damage, and
- 0.01 probability of at best severe structural damage, and
- 0.00 probability of collapse (Kircher and McCann, 1983).

The key to reading fragility curves is to keep in mind that each curve plots a single damage state and the probability that this state will be reached or exceeded with increasing levels of motion, proceeding toward the right side of the graph. Curves with steeper

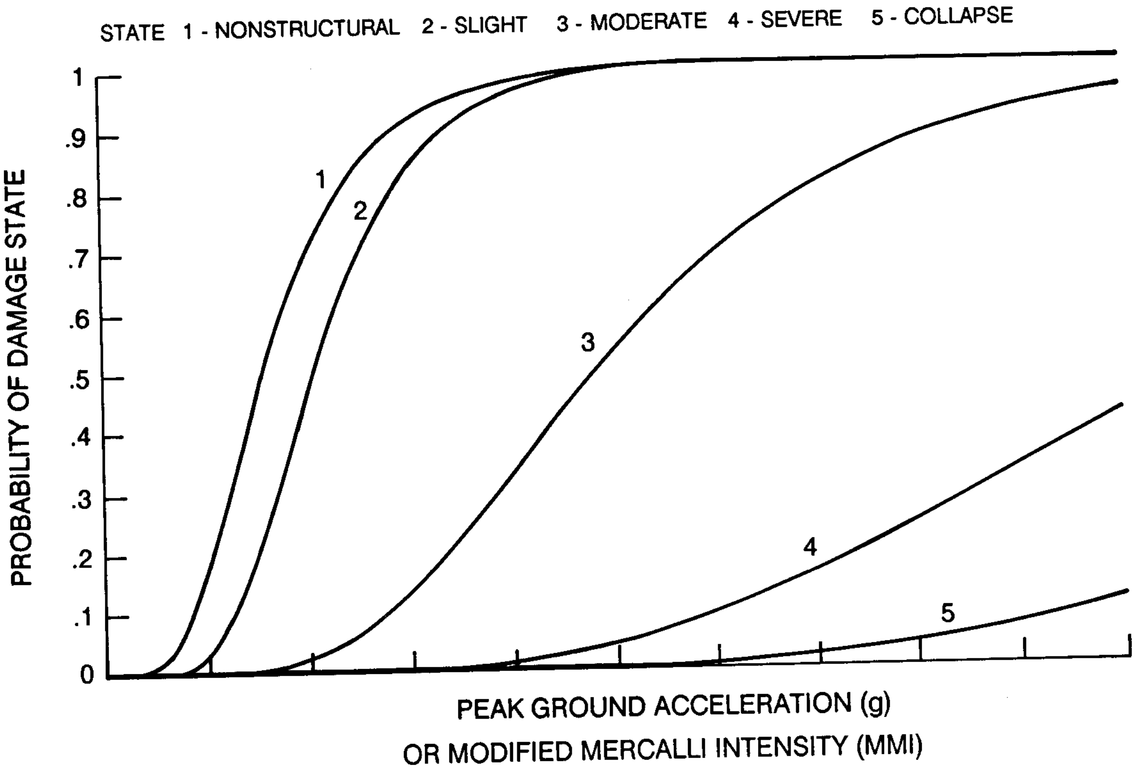

FIGURE E-3 **Fragility curves for wood-frame buildings. Source: Kircher and McCann (1983).**

slopes imply that those who developed the curves think there is less uncertainty in their estimate than for curves of flatter slope.

COMPARISONS BETWEEN METHODS

Table E-5 compares mean damage ratios for comparable ATC-13 and NOAA-USGS construction classes. Considering the various assumptions required in relating motion to loss, the different methods used to devise these motion-loss relations, and changing trends in construction and design codes, the comparison of the two methods in terms of average damage ratio shows the results to be remarkably close. For the first 10 damage ratios shown in Table E-5, the agreement is much better than for the remainder of the construction classes.

However, the relatively good agreement of the two methods does not necessarily establish accuracy for either. No method that is based on prior earthquake experience or expert knowledge of present and past construction practices can keep current with new construction types, changing code requirements, or changing concepts of quality control. Each earthquake tests existing structures, not the structures in design today or in the future.

Damage probability matrices can be converted into fragility curves. In Figure E-4, ATC-13 results for low-rise unreinforced-masonry buildings have been converted into fragility curves, and compared with JBA curves. For the lower damage levels, the two sets of curves are very similar. For the two highest damage levels, although the median values are similar the shapes of the curves are quite different. The steeper slope of the ATC-13 curves implies that the ATC-13 method concluded there was less uncertainty in estimating the probability of severe damage or collapse than did the JBA method.

While damage probability matrices can be converted into fragility curves, there is a difference in the supporting foundations upon which the motion-damage relationships were based in the studies. In the Six Cities study, calculations of structural capacities were made for a given class of construction. These defined the levels of motion (in units of acceleration, not intensity) at which only nonstructural damage would occur followed by, initial yielding, generalized yielding, and collapse. The steps are shown in Table E-6. This theoretical picture of the fragility of the structure was compared with available historical data, and the two analyses were compared and combined.

TABLE E-5 Comparison of Certain Building Damage Ratios, USGS as Compared to ATC-13 at MMI IX

ATC-13 Name	Number	Damage Ratio	USGS Curve	Damage Ratio	Comments
Wood frame (low)	1	8.8	1A	12	Old community
				9	New development
Light metal (low)	2	5.6	2A Small	6	
			2B Large	8	
Unreinforced masonry			5E	35	Unreinforced masonry
Bearing					
Low (1-3)	75	42			
Medium (4-7)	76	52.9			
Unreinforced masonry			4B	25	Vertical frame, nonbearing walls
Vertical frame					
Low (1-3)	78	27.5			
Medium (4-7)	79	33.1			
High (> 8)	80	44.5			
Reinforced concrete			3A	10 1/2	Steel moment-resisting frame
Shear wall/moment-resisting frame			4A	13	Concrete moment-resisting frame (assume ductile)
Low (1-3)	3	7.8			
Medium (4-7)	4	12.4			
High (> 8)	5	13.4			
Reinforced concrete			5D	23	Reinforced bearing walls
Shear wall/no frame					
Low (1-3)	6	12.1			
Medium (4-7)	7	15.2			
High (> 8)	8	22.6			
Reinforced masonry			5D	23	Reinforced bearing walls
Shear wall/no frame					
Low (1-3)	9	12.2			
Medium (4-7)	10	15.8			
High (> 8)	11	20.2			
Reinforced masonry			3A	10 1/2	Dual-steel
Shear wall/moment-resisting frame			4A	13	Dual-concrete (assume ductile)
Low (1-3)	84	8.7			
Medium (4-7)	85	10.8			
High (> 8)	86	13.9			
Tilt-up (low)	21	15.8	4D	30	

TABLE E-5 (Continued)

ATC-13 Name	Number	Damage Ratio	USGS Curve	Damage Ratio	Comments
Braced steel frame			3A	10 1/2	
Low (1-3)	12	9.6			
Medium (4-7)	13	11.3			
High (> 8)	14	14.0			
Perimeter steel			3A	10 1/2	CIP concrete walls
Moment-resisting frame			3B	17	Curtain walls
Low (1-3)	15	6.3			
Medium (4-7)	16	8.4			
High (> 8)	17	13.0			
Distributed steel			3A	10 1/2	CIP concrete walls
Moment-resisting frame			3B	17	Curtain walls
Low (1-3)	72	5.6			
Medium (4-7)	73	6.7			
High (> 8)	74	9.1			
Concrete ductile Moment-resisting frame/distributed			4A	13	
Low (1-3)	18	8.7			
Medium (4-7)	19	10.3			
High (> 8)	20	12.5			
Nonductile concrete			4E	27 1/2	
Moment-resisting frame			4D	30	
Low (1-3)	87	17.6			
Medium (4-7)	88	24.7			
High (> 8)	89	23.4			
Precast\no tilt-up			4D	30	Precast or lift slab
Low (1-3)	81	20.1			
Medium (4-7)	82	23.8			
High (> 8)	83	28.8			
Long span/low rise	91	6.6			
Mobile home	23	13.9	KVS	(13)	Extrapolated

SOURCE: Degenkolb (1986).

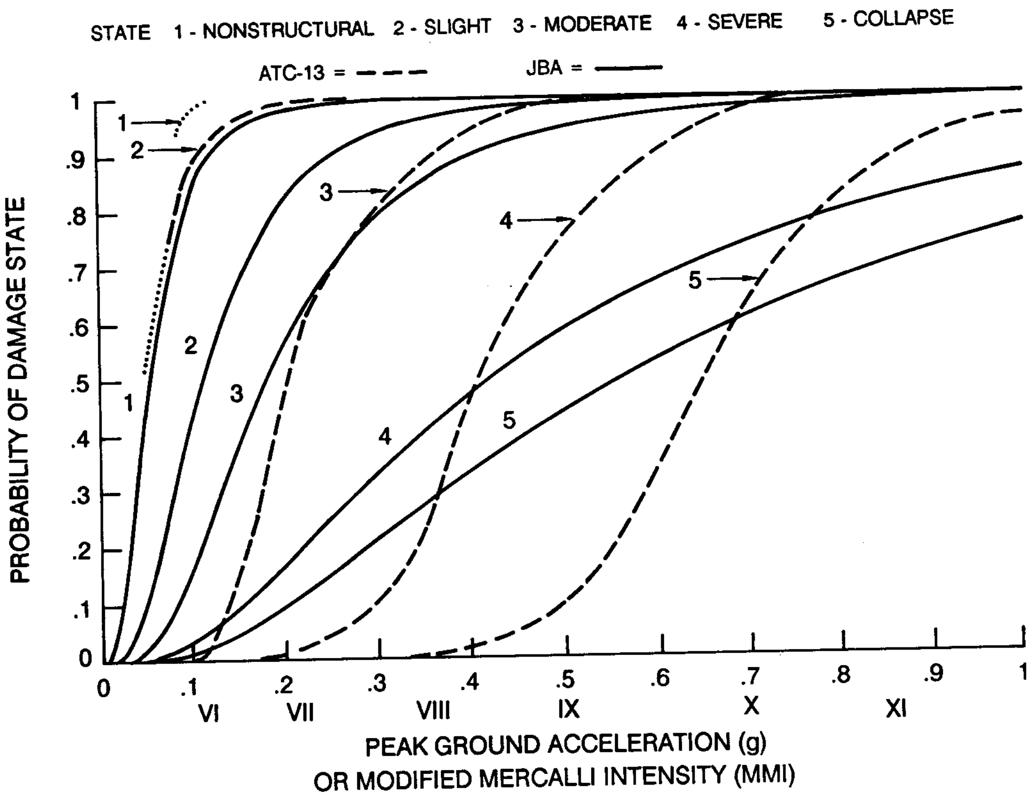

FIGURE E-4 Comparison of fragility curves for low-rise unreinforced masonry buildings from ATC-13 and JBA/Six Cities. Sources: ATC-13 data—Applied Technology Council (1985); JBA data—Kircher and McCann (1984).

TABLE E-6 Steps in Development of Fragility Curves Development Using Calculations and Engineering Judgment

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Building Acceleration Capacity Parameters

Step 1: Determine the basic geometry and structural properties of the building.

Step 2: Calculate the base shear capacity value for the building based on the working stress design (WSD) level of the code.

Step 3: Estimate the true WSD base shear capacity value for the building considering inherent design redundancies, and so on. This value represents the initiation of nonstructural damage.

Step 4: Calculate the base shear value for the building corresponding to the initial yield of the lateral-force resisting system. This value represents the initiation of slight structural damage.

Step 5 Calculate the base shear value for the building corresponding to the ultimate capacity of the main elements of the lateral-force resisting system. This value represents initiation of the severe structural damage threshold.

Step 6: Interpolate between the base shear value at initial yield (Step 4 results) and the base shear capacity at ultimate (Step 5 results) to determine the base shear value of the building corresponding to the general yielding of the lateral-force resisting system. This value represents the initiation of moderate structural damage.

Step 7: Estimate the base shear value for the building corresponding to the ultimate capacity of all lateral-force resisting elements. This value represents building collapse.

SOURCE: Kircher and McCann (1984).

In the ATC-13 study, only expert opinion was used to formulate damage probability matrices. In the earlier work of Whitman et al. (1973) and Martel (1964), historical data (from the 1971 San Fernando and 1933 Long Beach earthquakes, respectively) were the basis of damage probability matrices.

Thus, while the Six Cities method used fragility curves, it also used the approach of defining a standard or archetypical building for each construction class. (Actually, three archetypes—superior, median, and poor—were developed for each of the seven building classes and nine nonbuilding structures.) Calculations were then made as a basis for estimating realistic structural capacities, defined in terms of initial yielding, generalized yielding, and collapse. Though detailed, these calculations contained approximations because it is difficult in practice to estimate these capacities (Sharpe et al., 1982). Historic loss data were then assembled to compare with the theoretical results, with the final fragility curves being a compromise between the two.

The careful definition of standard structures—ideally with a picture and diagram of the actual or hypothetical building that is the standard—allows for the framework of the motion-damage debate or solicitation of expert opinion to be well defined. This method is also designed to accommodate a division of labor. As in other studies, the earthquake engineering was primarily a task accomplished by California structural engineers; then the inventory work was accomplished by local (Memphis) engineers, using the well-defined standard buildings as their guide to rating earthquake resistance.

Another use of carefully defined standard or archetypical buildings is the work of Gauchat and Schodek (1984), where earthquake engineers' opinions were solicited concerning the vulnerability of dwellings that were precisely defined with drawings and descriptions of materials. Figure E-5 shows the level of detail of the description of one construction class (one of six low-rise housing types defined in the study's inventory phase; captions for the construction details, tabular data relating to building codes, and other information are not shown in Figure E-5). This detailed description of construction classes allows the use of expert opinion to be focused on the same precise question and also allows other investigators to apply or convert the motion-damage relationships with confidence as to the departure point. All three other major methods reviewed here could benefit from this careful documentation of construction class definitions.

Malik (1986) argues that in the case of the ATC-13 project, "It is not clear what each expert considered to be the overall characteristics of a given classification of buildings" because the questionnaires only defined the classes by a short name. "(I)t is impossible to determine how much of the wide variability in the expert opinion is due to differing opinions regarding the overall characteristics of the building

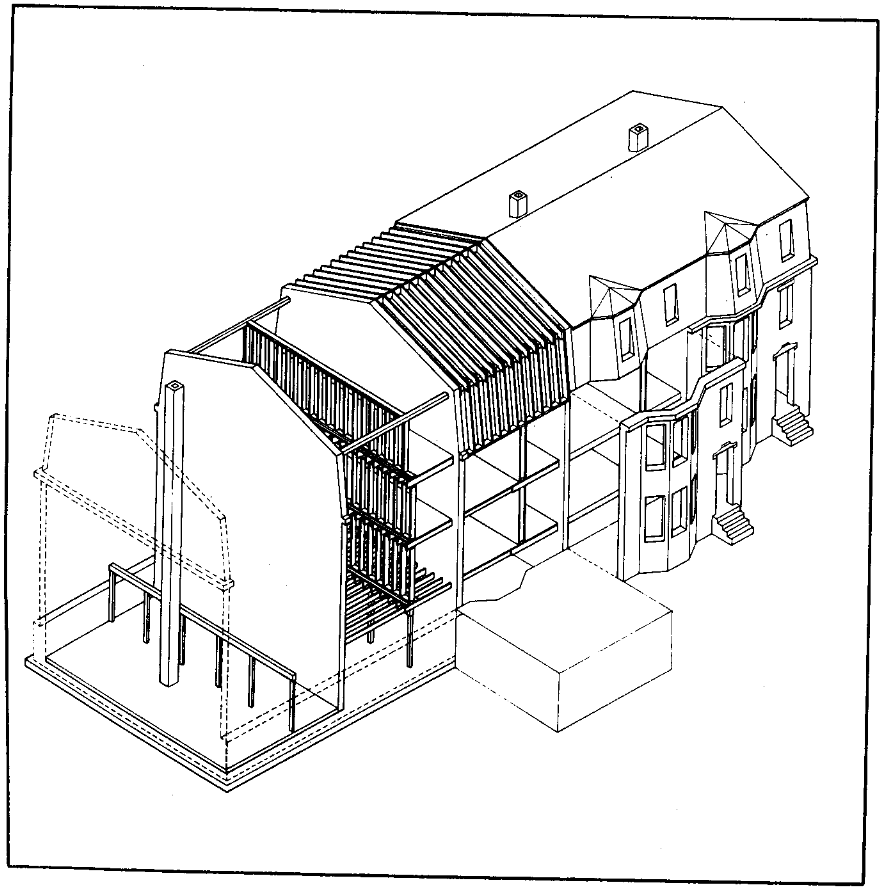

FIGURE E-5 Definition of one construction class (attached three-story rowhouse). Source: Gauchat and Schodek (1984). Foundations: A continuous basement wall of brick supports the party and exterior walls. The interior load bearing lines are supported by a main beam resting on brick piers. Footings are made of large flat rubble stones. (See A, B, C, D.) Exterior Walls: An exterior brick wall wraps the front and rear of the building which is divided into living units by solid brick party walls. The party walls are bonded to the wrapping exterior brick walls by a series of metal ties. Brick walls are finished with wood lath and plater. (See E, F.) Interior Walls: Interior party walls are made of solid masonry. For interior partitions, typical platform framing is used. Interior walls consist of 2″ x 4″ studs covered with lath and plaster. (See G, H, I, J.) Floors and Roof: Floors are simply supported 2″ x 10″ (full dimension) members sheathed by diagonally laid 1″ x 6″ sheathing and 1″ finish flooring. Roofs are 2″ x 8″ members sheathed with diagonally laid 1″ x 6″ sheathing and finish roofing. (See K, L, M, N.)

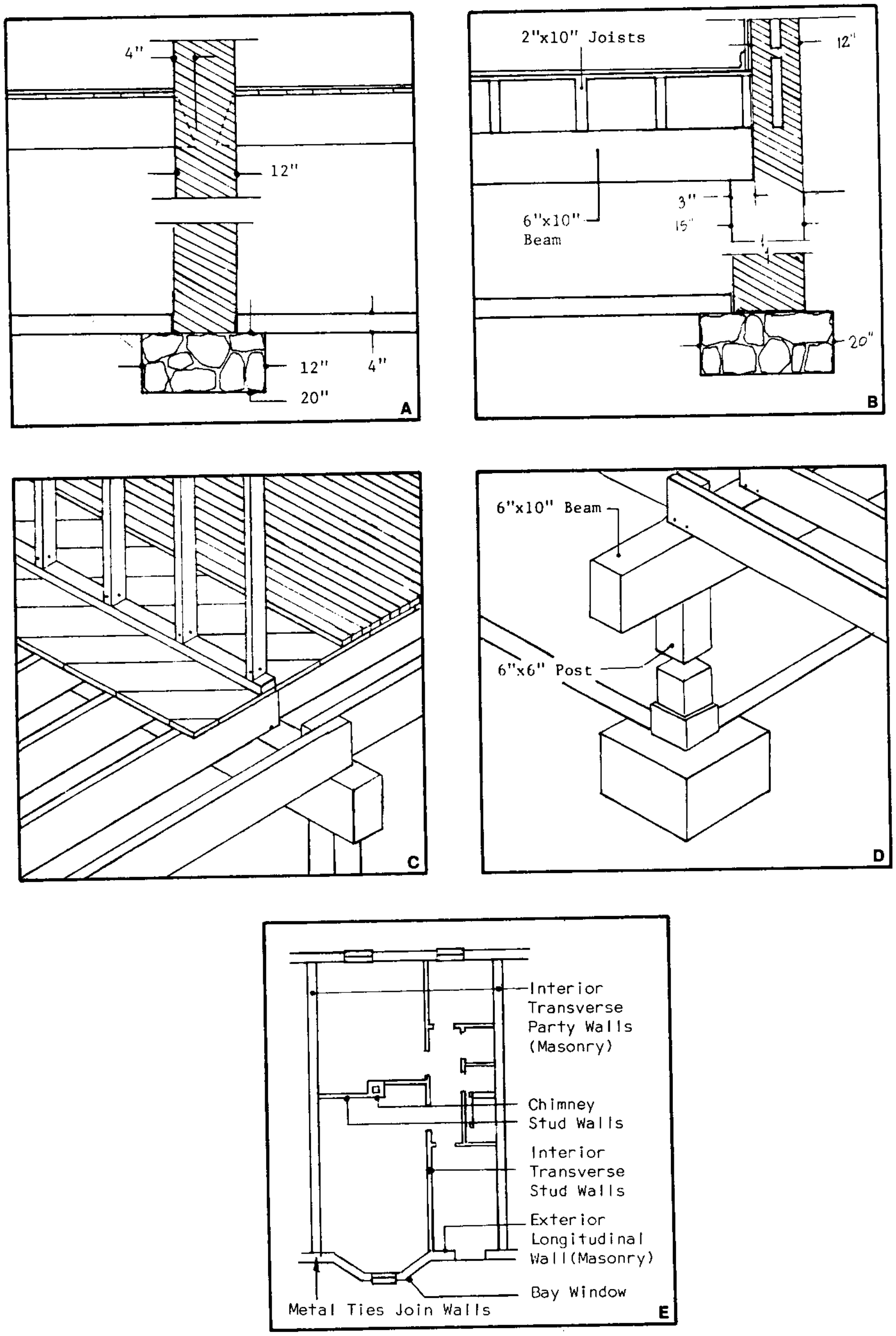

FIGURE E-5 (Continued).

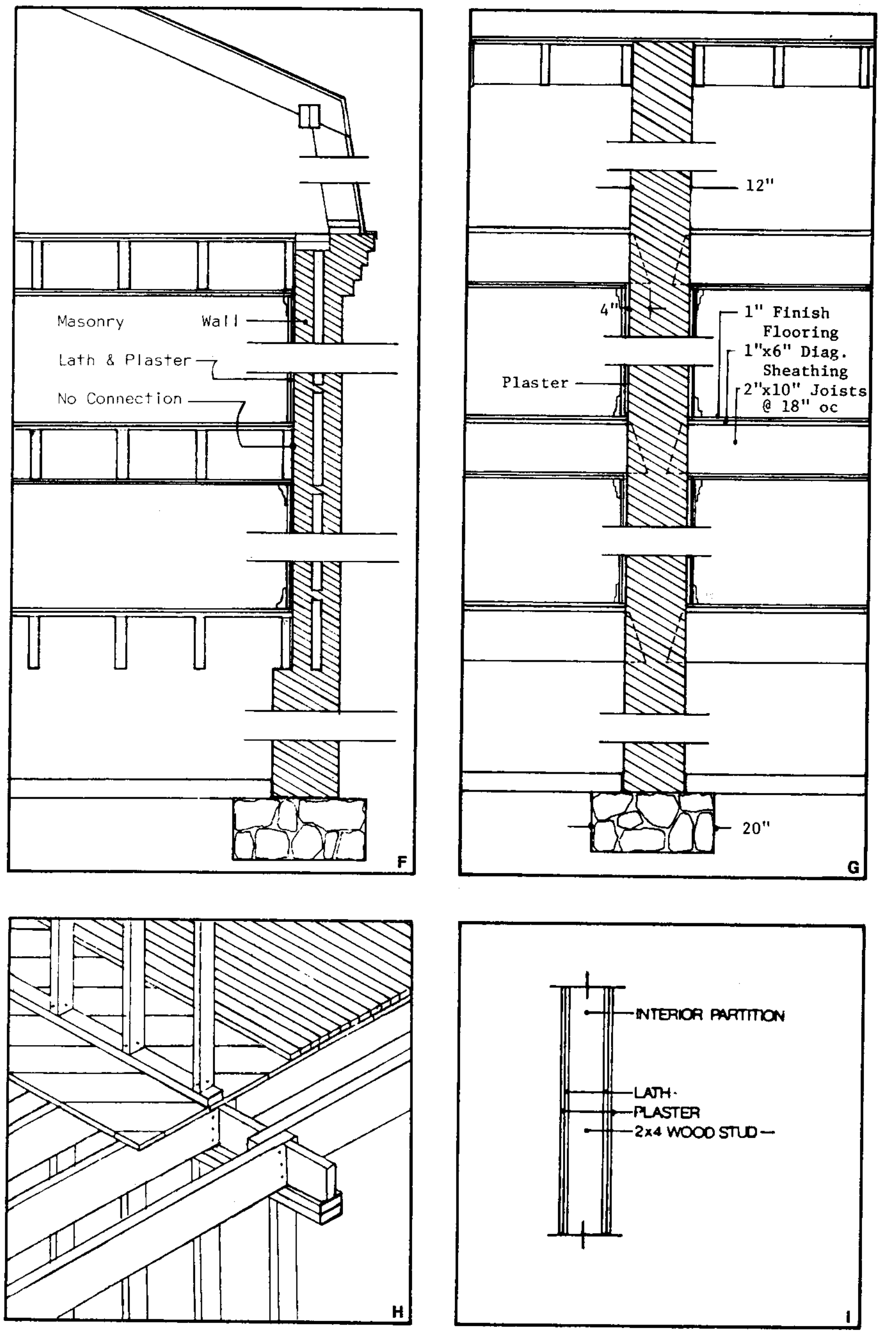

FIGURE E-5 (Continued).

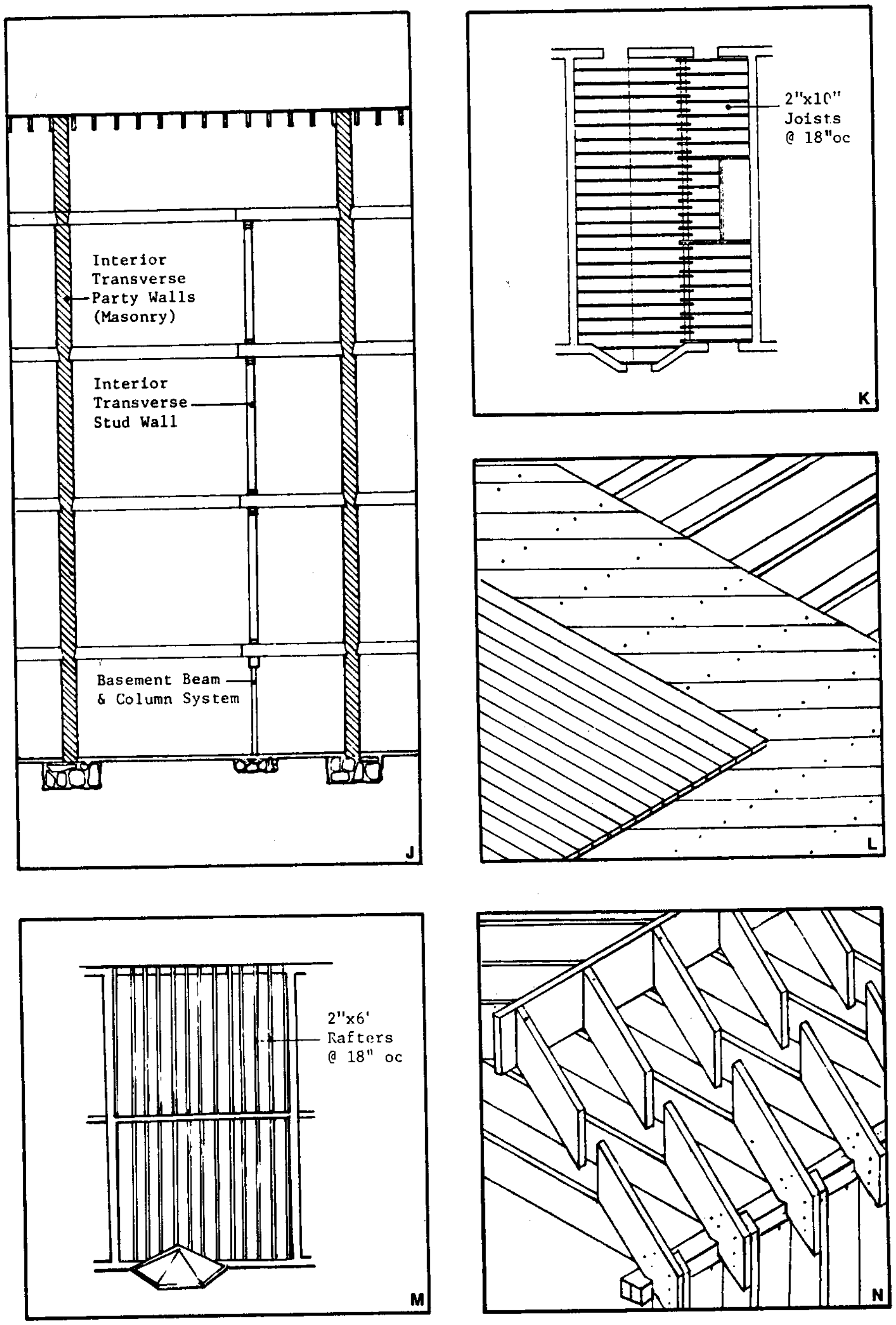

FIGURE E-5 (Continued).

stock," as compared to differences of interpretation of the definition of each class or of the MMI levels.

The most critical comment applicable to these earthquake loss estimation techniques is really a statement of the limitation of the state of the art rather than a critique of any individual method. A great deal of judgment and approximation are used to make up for the lack of definitive or hard data. The historical data on earthquake damage and losses are quite scarce as compared with the amount of data available in many other fields where loss or risk estimates are produced, such as with floods, fire, automobile accidents, and disease. This is the basic problem faced by all earthquake loss estimation methods. As Arnold (1985) notes, earthquake loss estimation methods are cheap but the information required to make them work is expensive.

Every method must face the question of where to limit itself in attempting to produce quantitative estimates—how far to push expert opinion, educated guesses based on suggestive but inconclusive data, or relatively untested extrapolations. This relates to the needs of those who will use the study, and while it has been stated in Working Paper B that these user needs should drive the study and determine its scope and methods, it is also true that the users must very realistically assess how much they really need to know, how much information they will really put to practical use, and how reliable this information must be. How much should be attempted?

There is little doubt that large-scale, multipurpose loss estimates must produce more than property loss estimates (e.g., casualties are very important), and certainly these estimates must extend beyond housing. Property loss estimates for dwellings, at least where the dwelling stock is relatively homogeneous as in California, are perhaps more a matter of science than art, but beyond this, loss estimation becomes much more art than science. Because any method selected must venture beyond the relative shallows of estimating dwelling property losses into deeper waters, this question of how far to venture will always arise. No large-scale application has yet to attempt quantitative, precise earthquake-caused fire or hazardous materials release losses, for example, because there seems to be a consensus among experts presently that quantitative loss estimation for these secondary or ensuing hazards is more appropriately kept in the realm of research rather than put before the public as credible forecasts upon which to base behavior. Users want detailed forecasts of every possible effect, and yet they also demand accuracy. Qualitative statements identifying high-risk areas or high-risk factors may be a suitable substitute.

The ATC-13 method is the most ambitious to date in several key respects:

- The number of construction classes;
- The number of use classes;
- Reliance on structured expert opinion to produce motion-damage and damage-loss relationships; and
- Extrapolation from nonconstruction (socioeconomic) data to synthesize an inventory.

Each of these four aspects was largely determined by the original scope of the study–for example, the need to enumerate every individual facility by construction and use class, because of the requirements of the intended economic use and the decision to rely primarily on presently computerized FEMA data. If the method is now to be applied or adapted to different uses, each of these four aspects requires re-evaluation and revision.

1. *Construction classes.* The number of construction classes could be reduced to be closer to that in the NOAA-USGS system, at least for buildings. Fewer lifeline or nonbuilding structure classes might be warranted as well, although dealing with these classes in a manner parallel to that for buildings is generally valid and is one of the significant contributions of the ATC-13 effort.
2. *Use classes.* The number of use classes could be greatly reduced, because for most emergency planning and hazard reduction purposes, the fine distinctions between various commercial and industrial economic sectors will not be used. In some cases, greater definition of essential emergency services facilities would be desirable, but this relates to facility-specific field surveys that are not discussed in ATC-13.
3. *Reliance exclusively on expert opinion.* In attempting fewer predictions, less expert opinion would be needed. For example, to forecast the number of days after the earthquake when 30 percent, 60 percent, and 100 percent of pre-earthquake function is restored for each of 60 use categories (an expanded version of the 35 use or social functions is used for this purpose), and for each of six damage states, 1,080 judgmental answers are needed: 3 functional levels × 6 use categories × 6 damage levels = 1,080 judgments.

If the method will be used to evaluate the hazards of unreinforced-masonry buildings in local jurisdictions, use of the historic data available and the increasing number of building-specific structural evaluations of such structures in communities with retroactive ordinances would seem to be obvious information sources to incorporate into a method. ATC-13's original broad scope does not make it the best method for such specific application.

4. *Extrapolation of inventory data.* Although the synthesis of construction data from economic or social data bases is to some extent necessary in any method, ATC-13's extensive reliance on this approach, primarily for budgetary reasons, emerges as a limitation. Other large-scale loss estimation studies have afforded the cost of at least some fieldwork to assemble information on key facilities, to sample areas to develop extrapolations that can be relied on as valid for a particular region's inventory of facilities, and to check at least some of the existing file data's accuracy.

The above critique has emphasized the weak points of ATC-13, but the project also resulted in some impressive accomplishments. The ATC-13 final report combines in one volume more data, a more comprehensive review of possible methods, and more discussion by experts of the various tasks involved in the earthquake loss estimation process than any other single publication. To some extent, the admirable degree to which the ATC-13 project documented each step of its method is the reason why criticism can be so precisely aimed at its weak points—the transparency allows the critic to see its blemishes as well as its attractive aspects. In this respect, the ATC-13 method is much superior to the NOAA-USGS and Six Cities studies discussed in this working paper, and allows independent investigators to analyze and evaluate each detail of the method in a very useful way.

While the NOAA-USGS literature makes frequent references to the fact that judgment has been used, these references are not so explicit as to allow investigators unconnected with these studies to replicate the results. Historical loss data are relied on to a much greater extent than expert opinion. Moreover, no indication is given as to how expert judgment was structured, whereas the ATC-13 method devoted considerable effort to an explicit process of structuring the opinions of its expert team. Hence, one of the reasons the ATC-13 study was launched was that "the body of historical damage data for earthquakes was largely proprietary and not publicly available" (Wilson, 1987).

The NOAA-USGS method, were its publications to define as explicitly the numerous judgments needed to interpret data or produce relationships based on expert opinion where data are lacking, would probably be seen to have comparable weaknesses to ATC-13. The NOAA-USGS method does not attempt to provide estimates of the loss of function experienced by many different economic sectors, to estimate equipment damage in buildings, or to analyze lifeline outages in a quantitative manner comparable to buildings. Due to its less ambitious scope and less explicit documentation, these NOAA-USGS weaknesses are less apparent.

In summary, the ATC-13 expert opinion method documents at least some of its uncertainties, while these are left quantitatively untreated in the NOAA-USGS reports. The fragility curve approach of the Six Cities study also attempts to portray at least some of its uncertainties. Whether damage probability matrices or fragility curves are the best way to represent loss estimates is an issue apart from the point that the explicit accounting for uncertainty must be attempted by all methods.

RELATIONSHIP OF DAMAGE TO PROPERTY LOSS

Steinbrugge (1986) discusses several complications in the property loss estimation process. Property damage may be repaired by hiring contractors ("impersonal loss" cost basis), or the owners of buildings (especially lightly damaged dwellings) may perform their own work ("personal" basis). For the 1971 San Fernando earthquake, his calculated difference between losses on a personal or impersonal loss basis amounts to $17 million in 1971 dollars.

The difference between defining property loss as the cost of repair or reconstruction divided by replacement cost, or as a percentage of cash value, can also be very large. McClure (1967) found that the actual cash value of dwellings in Bakersfield at the time of the 1952 Kern County earthquakes was only about a third of their replacement cost, and thus losses calculated on a replacement cost basis would have been about three times greater than if calculated on a cash value basis. (With wood-frame dwellings, where the accuracy of loss estimation is generally considered to be well developed, this is a large difference.)

The definition of actual cash value, of great interest in some legal proceedings, is also variable. For legal purposes in some states this is defined as the present market value, while in others it is the replacement cost less depreciation.

In spite of these difficulties, the translation of damage estimates into property loss estimates is easier than the task of translating damage into either casualty or functional loss estimates.

RELATIONSHIP OF DAMAGE TO CASUALTIES

Of all the kinds of loss to be estimated by a study, casualties are perhaps the most important to emergency services organizations and agencies. The data on casualty experience in individual buildings are more anecdotal than is the case with property loss. While there has never been a total collapse without an accompanying property loss of nearly 100 percent (depending on the definition of property loss as discussed above), there have been many buildings that have completely "pancaked" and yet have not hurt anyone simply because the earthquake occurred when the building was empty. Even when buildings are fully occupied at the time of the earthquake, the casualty ratios may differ greatly for the same damage level. This suggests that the casualty experience in previous earthquakes in a larger number of buildings must be collected and analyzed than in the case of relating property loss to damage. At this time, data that relate building damage to casualties are almost nonexistent. Three pages in the ATC-13 report (257–259) provide most of the known information.

The casualty-estimation method used in most large-scale studies is to consult overall (city-wide or larger) casualty statistics from previous earthquakes, rather than to relate casualties directly to damage or property loss estimates. The NOAA-USGS studies, for example, generally applied one casualty rate to wood-frame dwellings and one or more other rates to other kinds of construction.

While the overall fatality rate in any of the U.S. metropolitan area studies has always been less than 1 percent, the relative difference between 0.1 percent and 0.2 percent, for example, is a doubling of the predicted fatalities. In the NOAA-USGS studies, serious injuries that would require hospitalization were estimated at four times the number of fatalities, and thus the spread in the number of injuries predicted could fluctuate widely based on a seemingly small fatality ratio difference. Data collected from a larger number of earthquakes, with the type and degree of injury related to the physical damage that caused it, may slowly refine this state of the art.

RELATIONSHIP OF DAMAGE TO FUNCTIONAL LOSS

Of the three basic kinds of loss, functional loss is the most difficult to relate to damage. In the case of lifelines, areawide average outages from past events are often used, adjusted for local conditions, to reach a first approximation of the functional loss problem. For losses caused by building damage, the methods reviewed above attempt to associate a damage level with functional loss, in some cases inexplicitly (NOAA-USGS), in some cases explicitly (ATC-13). As the ATC-13 report notes, data are insufficient to allow for a statistical approach, so the relationships are based on judgments of how severely affected various occupancies or uses would be by various levels of damage. The same engineers selected for their expertise on predicting damage were used to develop these relationships.

Estimates of homelessness are a form of functional loss projection. The NOAA-USGS method assumed that a 50 percent dwelling damage ratio was the indicator that the building could not be occupied, resulting in homelessness and a need for alternative shelter. While the NOAA-USGS method is usually said to be a mean damage ratio method, the estimation of homelessness required a representation of the spread of the building damage levels.

This distribution was obtained primarily from the distribution pattern of damage for the 1933 Long Beach and 1971 San Fernando earthquakes. The 1969 study by Steinbrugge et al. on dwelling losses was also used, and this study essentially used a damage probability matrix: for each MMI, and for each damage ratio range, the percentage of buildings falling in that MMI/damage cell was produced. This indicates that seemingly clear lines of demarcation between different methods become blurred on closer examination and emphasizes the potential in developing hybrid methods that combine the best elements of different methods. The damage ratio-historical data (NOAA-USGS), damage probability matrix-expert opinion (ATC-13), and fragility curve-analysis of archetypes and historical data (JBA) approaches all have their strong and weak points.

The property loss-oriented studies of housing from past earthquakes "identify the dollar losses to wood frame dwellings but do not state at what damage level the houses were evacuated. Indeed, there probably was no consistent practice in this regard; in some earthquakes, social needs were sometimes confused with safety requirements when it came to buildings condemnations" (Algermissen et al., 1972).

Gulliver (1986) reviewed the relationships between damage ratio and building condemnation by local authorities that had been researched by Whitman (1974), Lee and Eguchi (1977), and the Office of Emergency Services (1979), and informally consulted some earthquake engineers. She concluded that a 20 percent damage ratio (with damage ratio defined in terms of replacement value) was the threshold past which homelessness would result.

In addition to homelessness caused by structural damage for both ground shaking and ground failure, Gulliver estimated homelessness caused by utility outage. Temporary homelessness was estimated according to intensity for eight construction classes, and permanent homeless caseload figures, related to irreparably damaged dwellings, were estimated for the higher damage ratios.

Evans and Arnold (1986) proposed a triage-based division of housing damage, defined in terms of habitability: habitable, temporarily uninhabitable, and permanently uninhabitable. Severe damage to a garage, porch, or deck would not affect the habitability of the adjacent single-family dwelling, and even severe structural damage might be repairable depending on the occupants' ability to finance the cost. Therefore, this classification system does not correlate homelessness with damage ratio or with overall damage level. The list of indicators assumed to match these three habitability states require dwelling-by-dwelling inspection, and this method is oriented toward postdisaster housing inspection procedures rather than loss estimation.

LIFELINES

Lifelines, or utilities and infrastructure systems, include railroad, motor vehicle, water, electricity, sewage, and communications services. The words systems and services are central to the distinction between the loss estimation process for lifelines as compared to buildings. Service outages are almost always a prominent concern addressed by lifeline studies. In many cases, the central concern with the estimation of damage to the building stock is to identify life safety or property risks. With some lifeline components, for example, dams that are part of a water system, life safety may also be a primary concern, but this does not apply to the majority of lifeline components. A lifeline such as a water or electrical utility's facilities and functions must be analyzed as a system rather than as separate, unrelated structures.

Loss estimation studies have seldom incorporated lifelines to the same extent as building losses. Lifeline loss estimation methodology is not as mature. Most lifeline earthquake engineering studies have either concentrated on deterministic evaluations of specific lifeline designs or on research into lifeline network analyses. The techniques used tend to be too complicated and time consuming for incorporation into a large geographic area loss estimation study. However, many recent loss estimation studies are attempting to incorporate lifelines into loss estimations. Future loss estimation studies should be encouraged to include lifelines partially for the purpose of aiding in the maturing of lifeline loss estimation.

Because the various components of a lifeline system are interrelated, lifeline loss estimation methods tend to rely on a probabilistic approach based on the idea of the reliability of networks. The network is defined in terms of serial (in-line, nonredundant) and parallel (redundant) components of the system, and the failure implications of individual components are analyzed in this context.

Applying a given level of conservatism to the evaluation of a single switchyard, the result of an expert's evaluation may be that a complete outage should be assumed for emergency planning purposes. Applying this judgment to all switchyards in an entire region, forecasting a 100 percent outage throughout the system would not necessarily be appropriate. This same expert, if asked to estimate the overall system's postearthquake capacity, would probably take into account that performance will vary among a large number of facilities, even if seemingly identical in construction characteristics and subjected to the same presumed intensity. The systems approach to lifeline loss estimation also can point out instances where the loss to a single facility could have a widespread effect throughout a system, far out of proportion to the size or property value of that one key facility.

The estimation of losses to the individual components of a lifeline system—the individual bridge, power transmission or radio tower, docks and quaywalls, and so on—has a less extensive historical loss experience data base than for buildings. The most ambitious attempt at developing classes that include nonbuilding structures is ATC-13 (Applied Technology Council, 1985), in which 38 of the 78 total construction classes are nonbuilding structures and most of these 38 classes are related to lifelines.

Lifeline service outage estimates can be stated in various ways. The simplest form of the estimate is to state, for example, that a certain segment of a highway route should be presumed either closed or open. A more complex statement, requiring more information and analysis to produce valid results, would be to assign a postearthquake traffic flow capacity to highway segments. This latter approach is unusual, but was used in a study of the San Francisco Bay Area's transportation system (Jones, 1983).

In the first of the urban-scale loss studies by NOAA, the essence of the telephone loss estimate was as follows:

> It is anticipated that 50 percent of the telephone system will be out of service in the counties of San Francisco, San Mateo, Santa Clara and Marin for an indefinite period of time due to equipment damage in the event of a magnitude 8.3 shock on the San Andreas fault. . . . Even without damage to the system, the lines will be overloaded and for all practical purposes it will be useless for telephoning in emergency situations. (Algermissen et al., 1972)

A California Division of Mines and Geology study of the same area and scenario earthquake, although with different scenario intensities, was done 10 years later (Davis et al., 1982b) and provided telephone outage statements with greater detail. The geographic breakdown of outage zones was approximately at the county scale, as for the earlier NOAA study, but the outage was estimated in terms of recovery patterns where the percentage of normal service was graphed versus the number of days after the earthquake. One of four different graphs or levels of outage was assigned to each county-sized zone.

Losses in the level of service provided by the lifeline should take into account a nonengineering factor that may be difficult to evaluate: the emergency response capability of the lifeline operator or of other emergency response agencies. A utility with an earthquake-resistant radio system, personnel who undergo annual earthquake exercises to test their ability to carry out preassigned tasks, and back-up plans for handling significant damage beyond that occurring in weather-related incidents, should be much more able to contain the impact of earthquake damage than another utility without these attributes.

The first of the large-scale loss estimates (Algermissen et al., 1972) established the basic table of contents followed by most other loss estimate studies. The categories of lifelines used were: communications (primarily radio, television, and telephone service, although newspaper and post office services were also briefly considered); transportation (railroads, highways, bridges, mass transit, airports, and ports); and public utilities (electricity, natural gas, water, sewage, and petroleum pipelines). There were 15 systems in all.

The Central U.S.-Six Cities loss study (Allen and Hoshall et al., 1985) used fragility curves to analyze individual lifeline components. Bridges, for example, were divided into five classes based on type and length of spans. Network analysis was used to relate the performance of individual components to overall performance of the system. Of the large-scale multipurpose loss estimation studies, this appears to be the most extensive use of network analysis to date. Network analysis has been more routinely used with one given lifeline system. The probabilistic analysis of the seismic risk faced by a gas utility's system in Utah, where 52 different earthquakes was considered, illustrates an approach that has become increasingly common in the field of lifeline earthquake loss analysis (McDonough and Taylor, 1986).

Reviews of the state of the art of lifeline earthquake analysis are found in the works of Eguchi (1984), Cooper (1984), Smith (1981), Shah and Benjamin (1977), Whitman et al. (1975), and Duke and Moran (1972). The Applied Technology Council (1985) reviewed the field in the process of developing ways to deal with the problem of estimating lifeline losses, and another broad review of the field from the hazard reduction perspective is provided by the Building Seismic Safety Council (1987).

The fact that the proceedings of the Eighth World Conference on Earthquake Engineering (Earthquake Engineering Research Institute, 1984) contain 14 papers on the topic and the American Society of Civil Engineering Technical Council on Lifeline Earthquake Engineering is engaged in numerous ongoing activities are signs of rapid growth in the field.

SUMMARY

As to the question of the accuracy or uncertainty of these methods, some opinions can be presented, although little is available concerning controlled, statistically valid comparisons of the results produced by different methods with the actual losses produced by earthquakes.

However expressed (e.g., curves or matrices), estimates almost always are used as single numbers. This is true for estimates of forces in engineering design—ultimately one force number is developed for design purposes. It is also true for estimates of casualties and property loss that are used for planning and earthquake awareness purposes.

The uncertainty contained in a loss study's motion-damage or damage-loss analysis method should be documented, as well as that of the seismic hazard and inventory components. When ranges of numbers are provided, however, many users will still need to select a single-value result—the best estimate or maximum estimate, for example. Many disaster planning, public education, and hazard reduction program development purposes require a single number on the bottom line of the analysis.

At present, accuracy is not great. A prudent claim would be to within a factor of one and one-half for single-family dwellings, a factor of three for commercial, industrial, and institutional buildings, and a factor of ten for areas with no recent earthquake history.*

The amount of systematic data for building damage is very small compared to the variety of conditions applying to any future earthquake. At present, typical estimating techniques relate a single, gross, structural parameter (construction class) to a single, gross, ground-motion parameter (intensity) to arrive at a damage estimate. The variety of parameters that in fact significantly affect building performance are indicated in Table E-7, for one class of construction. Clearly, with even a small uncertainty in each parameter, the cumulative uncertainty must be very large. At present however, there is little point in incorporating these additional parameters in estimating methods because matching damage data do not exist.

If the expected accuracy noted above is accepted, then a central concern is the relative accuracy of different methods of relating motion to damage cases. Significant improvements in the state of the art should be sought, but the users of loss studies should not expect dramatic improvements in the near future. Comparisons done so far indicate variations between methods to be well within the limits of overall accuracy. As shown in Table E-5, the most extreme discrepancy between the NOAA-USGS and ATC-13 estimates is for tilt-up structures, where ATC-13 shows a mean damage ratio of 15.8 percent, compared to 30 percent in NOAA-USGA. All other structural types show a much closer level of agreement.

Attempts to refine methods, such as greatly increasing the range and definition of structural types, will not improve accuracy until

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*These ranges have not been established on statistical grounds, and represent a consensus of the panel.

TABLE E-7 Damage Estimate Based on Simple Estimating Parameters Contrasted to Listing of All Factors That Affect Damage

	Building Description	Ground Motion	Damage Ratio
Estimate[a]	4A Reinforced concrete, superior	MMI IX	13 Percent
Reality	Height, low, medium, high Structural system types Concrete types and quality Building size Design of connection details Irregularity of plan Irregularity of elevation Building age (code) Building period	Acceleration Displacement Velocity Duration Frequency content Foundation type Soil type	Dispersion as indicated by DPM or fragility curve

[a] Example category from ISO classification.

damage information matches those structural types. The same is true for the effects of ground motion. Use of the Modified Mercalli Scale, with all its limitations, still matches the available damage information.

Working Paper F
Liquefaction and Landslides

LIQUEFACTION

As applied to seismic problems, liquefaction has become a catch-all word referring to various types of earthquake-caused failures of saturated cohesionless soils. Four different Manifestions of liquefaction have been identified (National Research Council, 1985):

1. Flow slides from slopes.
2. Loss of foundation bearing capacity, leading to large settlement and/or tilting of structures.
3. Lateral spreading, that is, a movement of gradually sloping ground toward low points.
4. Ground oscillation, where ground overlying saturated sand breaks up into jostling "plates."

All of these phenomena may be accompanied by sand boils—small volcanoe-like mounds or craterlets from which sand and water spurt to the surface.

The first two manifestations of liquefaction are dramatic but less common. When they do occur, there is considerable potential for damage and, in the case of flow slides, for loss of life. Flow slides may occur in natural ground, but are also likely in man-made deposits, such as earth dams, mine tailings dams, and fill placed behind waterfront retaining structures.

The remaining manifestations are less spectacular but much more common. Lateral spreading frequently disrupts pipelines, roads, railways, and canals, and if occurring beneath a structure, can cause extensive damage and even loss of life. Ground oscillation and associated sand boils can present an enormous clean-up problem if they occur in a built-up area. If accompanied by ground settlement, damage and disruption can also occur.

All aspects of seismic liquefaction have been reviewed and discussed in a major report (National Research Council, 1986). It is important, for the subsequent discussion, to distinguish two situations:

- Level ground where no shear stresses are required for equilibrium following an earthquake.
- Slopes (which include building foundations) where shear stresses are required for static equilibrium.

Ground with a very gentle slope ($< 5°$) may, depending on the circumstances, fall into either situation.

Liquefaction Susceptibility

A range of criteria and methods exists for evaluating the susceptibility of a soil to liquefaction as a result of earthquake ground shaking. The simplest method considers just two factors: the geologic age of the deposit and the depth to the water table. Table F-1 presents such a set of criteria from Youd et al. (1978). Other examples appear in ATC-13 (Applied Technology Council, 1985). These ratings are based on observations and experience during actual earthquakes, and rate the susceptibility of a soil deposit as a whole. Only portions of a deposit would actually experience liquefaction.

In Table F-1, latest Holocene refers to the most recent 1,000 years, with the earlier Holocene extending back to 10,000 years. Experience suggests that deposits older than about 130,000 years will not liquefy. As indicated, the depth of the water table is also a very important factor. The information in Table F-1 is directly useful for preparing liquefaction hazard maps. A procedure for combining this information with the expected ground-shaking hazard is described by Youd and Perkins (1978).

A more quantitative method for assessing liquefaction susceptibility makes use of penetration resistance as measured by the Standard Penetration Test (SPT). In Figure F-1, the horizontal axis is the blow count in the SPT, corrected for the depth at which the blow

TABLE F-1 Considerations Used in Producing a Map of Liquefaction Susceptibility in the San Fernando Valley

	Depth to Groundwater (ft)		
Age of Deposit	0-10	10-30	< 30
Latest Holocene	High	Low[a]	Nil
Earlier Holocene	Moderate	Low	Nil
Late Pleistocene	Low	Nil	Nil

[a] Latest Holocene deposits in this basin generally are not more than 10-ft thick. Saturated deposits in the 10- to 30-ft interval are earlier Holocene sediments.

SOURCE: Youd et al. (1978).

count is recorded and the energy delivered to the drill rods when performing the test. The vertical axis is the ratio of the dynamic stress occurring during an earthquake to the vertical effective overburden stress in the soil. The dynamic stress is commonly computed from a simple expression involving the peak acceleration at ground surface and the unit weight of the soil. The data points on the plot represent actual observations during earthquakes, and a curve has been drawn separating cases of liquefaction from those where no liquefaction was observed. If a new situation is represented by a point plotting above this curve, liquefaction is to be expected.

The data in Figure F-1 apply for an earthquake with a magnitude of 6.5. Corresponding curves have been developed for other magnitudes (see Figure F-2): the larger the magnitude, the greater the duration of shaking and hence the greater the susceptibility to liquefaction for a given $(N_1)_{60}$ and τ_{av}/σ'_o. These figures apply for clean sands; relations for taking into account the influence of fines have also been developed.

It is unlikely that a program of penetration tests would be undertaken in connection with a large-scale loss estimation study. However, data from previously drilled borings can be used to evaluate the liquefaction susceptibility of deposits in a study area and thus serve as a basis for preparing liquefaction hazard maps.

Other and more sophisticated methods for evaluating liquefaction susceptibility have also been developed. There are more precise techniques for measuring penetration resistance, such as the Cone Penetration Test (CPT). If very good undisturbed samples can be obtained, various types of laboratory tests can be done. Theoretical

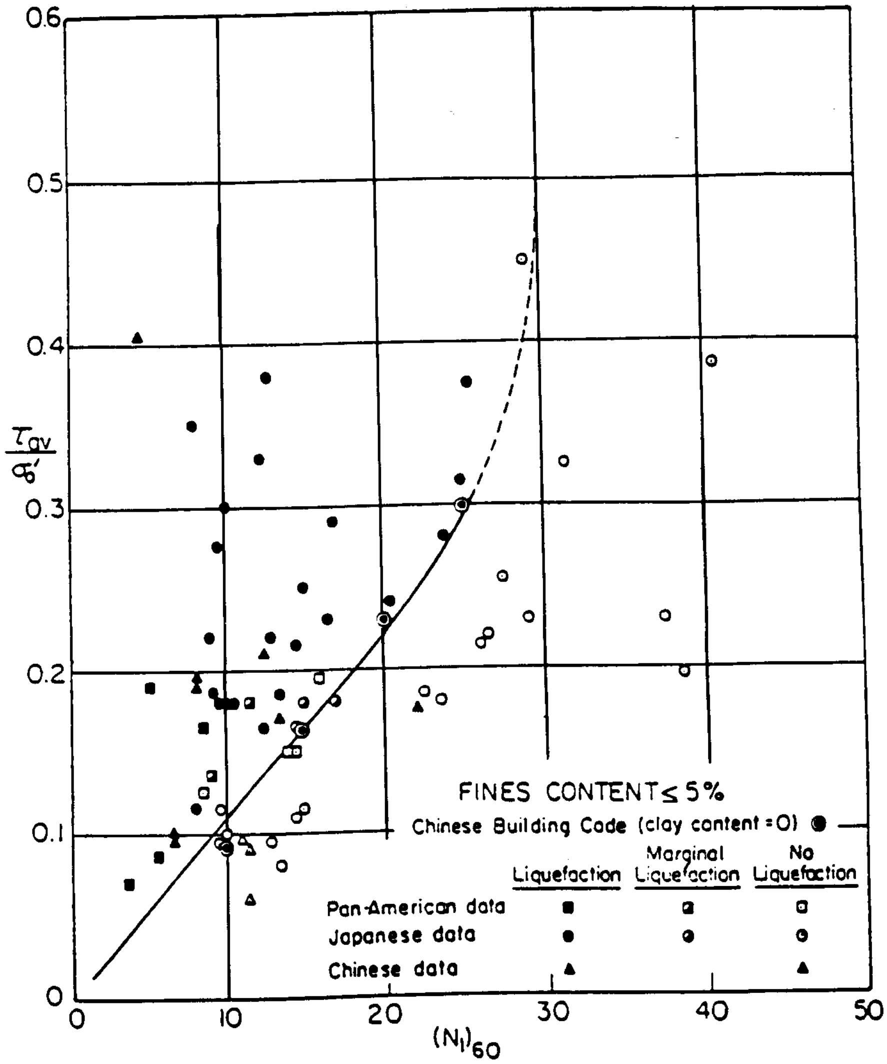

FIGURE F-1 Relationship between stress ratios causing liquefaction and $(N_1)_{60}$ values for clean sands for magnitude 7.5 earthquakes. Source: Seed et al. (1984).

methods are also available. While these techniques are of value for evaluating specific sites or particular earth structures (e.g., earth dams), they are not appropriate for large-scale loss estimation studies.

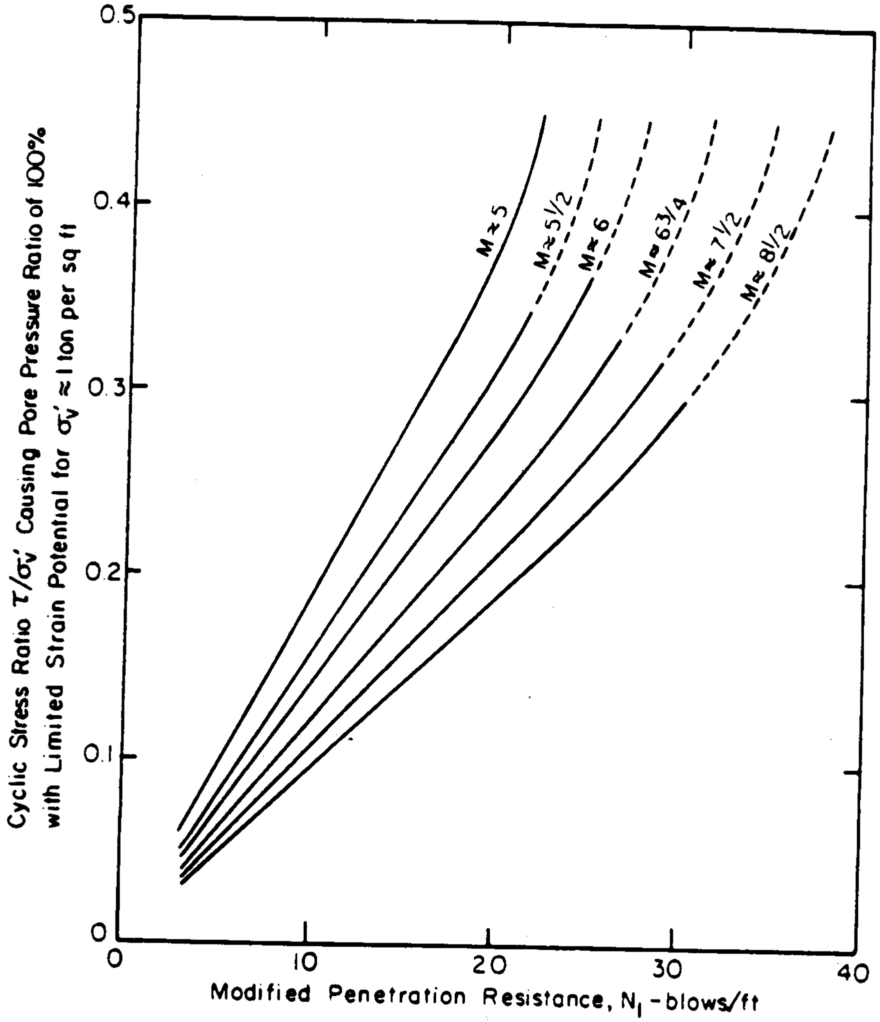

FIGURE F-2 Chart for evaluation of liquefaction potential of sands for earthquakes of different magnitudes. Source: Seed and Idriss (1982).

Consequences of Liquefaction

Methods for evaluating liquefaction susceptibility are essentially deterministic in nature, and do not indicate directly how likely liquefaction might be during an event of given intensity nor how widespread liquefaction might be over a given deposit. Furthermore, the methods are based heavily on observations as to the occurrence or nonoccurrence of some manifestation of liquefaction, without reference to the severity of the occurrences. Indeed, it is possible, even likely, that liquefaction actually occurred beneath the surface in some of the cases identified as "no liquefaction," but these liquefactions did not appear at the surface of the ground. Ishihara (1985) has shown that the thicknesses of a liquefying layer and of an overlying nonliquefiable layer both affect the likelihood that liquefaction is observed at the surface; Figure F-3 provides initial guidance in this matter.

The ATC-13 report gives a ground probability failure matrix, reproduced here as Table F-2, based on expert opinion. The matrix obviously is oriented to situations in California, but for comparable soils should also apply elsewhere. Liao et al. (1988) performed a detailed statistical analysis of the case studies upon which Figure F-1 is based. It was concluded that the boundary curve in Figure F-1 might correspond to about 50 percent probability of liquefaction. This study also provided curves for estimating the probability of liquefaction for a point falling at any point of a τ_{av}/σ_o' versus $(N_1)_{60}$ diagram. However, these several results still do not get at the questions of how widespread and damaging liquefaction may be for a given deposit.

In the ATC-13 report, some very scant data are cited to the effect that damage to buildings on poor ground (such as liquefiable sand) is 5 to 10 times greater than damage to buildings on firm ground, for the same intensity of ground motion. Thus, for facilities on the surface, the ATC report proposes to evaluate a mean damage ratio (MDR) as:

$$MDR_{ground} = MDR_{firm\ ground} \times P[L] \times 5,$$

where $P[L]$ is the probability of liquefaction for the deposit of interest. For buried structures (e.g., pipelines), the ATC report proposes using a factor of 10.

Youd and Perkins (1987) introduce the concept of a liquefaction severity index (LSI). They relate LSI to the extent and magnitude of movements and other manifestations of liquefaction that can be expected; their descriptions are reproduced in Table F-3. They also propose an equation relating LSI to the magnitude and epicentral distance for an earthquake. However, this equation is applicable only for late Holocene floodplains and deltas associated with rivers having channel widths greater than 10 meters and for seismic conditions in California and Alaska. Thus the method is not directly applicable to other parts of the country. In addition, the method still leaves

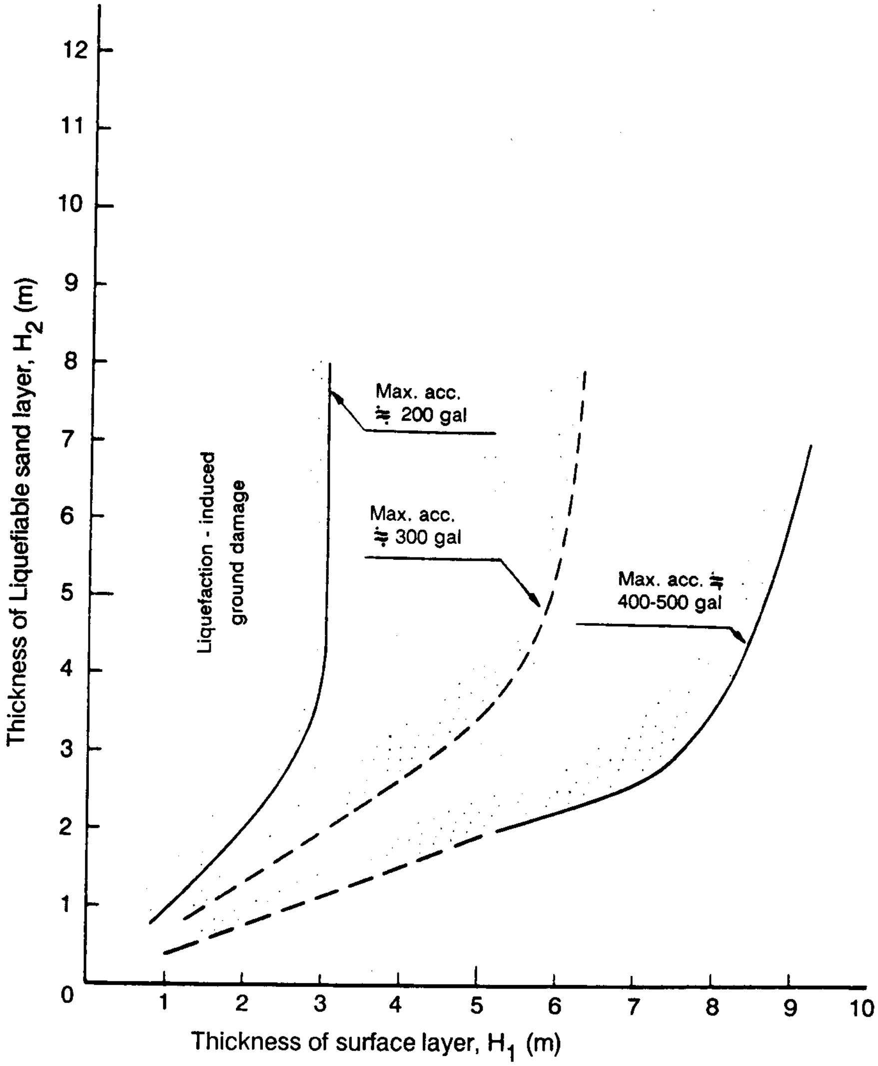

FIGURE F-3 Proposed boundary curves for site identification of liquefaction-induced damage. Source: Ishihara (1985).

the problem of relating LSI to quantitative measures of damage to facilities.

LANDSLIDES

Earthquake-induced landslides have caused tens of thousands of

TABLE F-2 Ground Failure Probability Matrix for Poor Ground (in percent)[a]

		Probability of Ground Failure by MMI						
Zone	Type of Deposit	VI	VII	VIII	IX	X	XI	XII
1a	Stream channel, tidal channel	5	20	40	60	80	100	100
1b	San Francisco Bay mud and fill over bay mud	3	15	30	40	60	80	90
2a	Holocene Alluvium, water table shallower than 3 m (10 ft)	2	10	20	30	40	60	80
2b	Holocene Alluvium, water table deeper than 3 m (10 ft)	0.5	2	5	7	12	25	40
3	Late Pleistocene Alluvium	0.1	0.5	1	2	4	7	10

[a] Estimates are based on consensus of the ATC-13 Project Engineering Panel.

SOURCE: Applied Technology Council (1985).

deaths and billions of dollars of losses worldwide in this century. In many earthquakes the resulting landslides have caused as much or more damage than the other effects of ground shaking. Over half of the damage caused by the 1964 Alaska earthquake was the result of landslides. In Japan, of the deaths caused by large earthquakes since 1964, more than half have been attributed to landslides. In an earthquake in the Peruvian Andes in 1970, an avalanche was triggered that buried two cities and killed at least 20,000 people. The 1987 earthquake in Ecuador caused landslides that clogged rivers and destroyed sections of the trans-Andean oil pipeline.

In 1959, the Hebgen Lake, Montana earthquake set off a mammoth landslide that dammed the Madison River. Major efforts were made to reduce the possibility of rapid erosion when this natural dam was overtopped, to prevent catastrophic downstream flooding. The 1971 San Fernando earthquake caused very damaging slides in earth dams and structural earthfill in the western part of the San Fernando Valley—most of which were associated with liquefaction. In addition there were several hundred rockfalls, soil falls, and debris flows that caused considerable damage to highways and roads. Blockage of roads is a common occurrence whenever earthquakes shape steep terrain.

TABLE F-3 Qualitative Assessment of Abundance and General Character of Liquefaction Effects as a Function of LSI for Areas with Widespread Liquefiable Deposits

LSI	Abundance and General Character of Liquefaction Effects
5	Very sparsely distributed minor ground effects include sand boils with sand aprons up to 0.5 m (1.5 ft) in diameter, minor ground fissures with openings up to 0.1 m wide, ground settlements of up to 25 mm (1 in.). Effects lie primarily in areas of recent deposition and shallow groundwater table such as exposed stream beds, active flood plains, mud flats, shore lines, and so on.
10	Sparsely distributed ground effects include sand boils with aprons up to 1 m (3 ft) in diameter, ground fissure with openings up to 0.3 m (1 ft) wide, ground settlements of a few inches over loose deposits such as trenches or channels filled with loose sand. Slumps with up to a few tenths of a meter displacement along steep banks. Effects lie primarily in areas of recent deposition with a groundwater table less than 3 m (10 ft) deep.
30	Generally sparse but locally abundant ground effects include sand boils with aprons up to 2 m (6 ft) diameter, ground fissures up to several tenths of a meter wide, some fences and roadways noticeably offset, sporadic ground settlements of as much 0.3 m (1 ft), slumps with 0.3 m (1 ft) of displacements common along steep stream banks. Larger effects lie primarily in areas of recent deposition with a groundwater table less than 3 m (10 ft) deep.
50	Abundant effects include sand boils with aprons up to 3 m (10 ft) in diameter that commonly coalesce into bands along fissures, fissures with widths up to 1.5 (4.5 ft), fissures generally parallel or curve toward streams or depressions and commonly break in multiple strands, fences and roadways are offset or pulled apart as much as 1.5 m (4.5 ft) in some places, ground settlements of more than 1 ft (0.3 m) occur locally, slumps with a meter of displacement are common in steep stream banks.
70	Abundant effects include many large sand boils (some with aprons exceeding 6 m [20 ft] in diameter that commonly coalesce along fissures), long fissures parallel to rivers or shorelines usually in multiple strands with many openings as wide as 2 m (6 ft), many large slumps along streams and other steep banks, some intact masses of ground between fissures displaced 1-2 m down gentle slopes, frequent ground settlements of more than 0.3 m (1 ft).
90	Very abundant ground effects include numerous sand boils with large aprons, 30 percent or more of some areas covered with freshly deposited sand, many long fissures with multiple strands parallel streams and shore lines with openings as wide as 2 or more meters, some intact masses of ground between fissures are horizontally displaced a couple of meters down gentle slopes, large slumps are common in stream and other steep banks, ground settlements of more than 0.3 m (1 ft) are common.

SOURCE: Youd and Perkins (1987).

TABLE F-4 Relative Abundances of Earthquake-Induced Landslides in 40 Historical Earthquakes Worldwide[a]

- Very abundant (> 100,000):
  - Rock falls
  - Disrupted soil slides
  - Rock slides
- Abundant (10,000 to 100,000):
  - Soil lateral spreads
  - Soil slumps
  - Soil block slides
  - Soil avalanches
- Moderately common (1,000 to 10,000):
  - Soil falls
  - Rapid soil flows
  - Rock slumps
- Uncommon (100 to 1,000):
  - Subaqueous landslides
  - Slow earth flows
  - Rock block slides
  - Rock avalanches

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[a] Landslide type listed in order of decreasing total numbers.

SOURCE: Wilson and Keefer (1985).

An excellent, recent summary about earthquake-induced landslides and their consequences has been prepared by Wilson and Keefer (1985). Table F-4 assembles data concerning the relative abundance of different types of landslides, while Table F-5 categorizes different types of earthquake-induced landslides together with their characteristics.

Likelihood of Landslides

Information relating the occurrence of landslides to characteristics of earthquakes has been summarized in ATC-13 (Applied Technology Council, 1985). Building on a concept proposed by Legg et al. (1982), and utilizing expert opinion, ATC developed the probability matrices reproduced in Table F-6. Each box in this table represents a different degree of inherent stability for a slope, characterized numerically by the yield acceleration, a_c, at which movement starts. The slope failure states (SFS) relate, in a probabilistic manner, landslide displacement to shaking intensity as a function of initial slope stability. The matrices are for dry summer conditions in California;

TABLE F-5 Characteristics of Earthquake-Induced Landslides

			Water Content					
Name	Type of Movement	Internal Disruption[a]	Dry	Moist	Partly Saturated	Saturated	Velocity[b]	Depth[c]
			Landslides in Rock					
Disrupted slides and falls								
Rock falls	Bounding, rolling, free falling	High or very high	X	X	X	X	Extremely rapid	Shallow
Rock slides	Translational sliding on basal shear surface	High	X	X	X	X	Rapid to extremely rapid	Shallow
Rock avalanches	Complex, involving sliding and (or) flow as stream of rock fragments	Very high	X	X	X	X	Extremely rapid	Deep
Coherent slides								
Rock slumps	Sliding on basal shear surface; component of headward rotation	Slight or moderate	?	X	X	X	Slow to rapid	Deep
Rock block slides	Translational sliding on basal shear surface	Slight or moderate	?	X	X	X	Slow to rapid	Deep

TABLE F-5 (Continued)

			Water Content					
Name	Type of Movement	Internal Disruption[a]	Dry	Moist	Partly Saturated	Saturated	Velocity[b]	Depth[c]
		Landslides in Soil						
Disrupted slides and falls								
Soil falls	Bounding, rolling, free falling	High or very high	X	X	X	X	Extremely rapid	Shallow
Disrupted soil slides	Translational sliding on basal shear surface or zone of weakened, sensitive clay	High	X	X	X	X	Moderate to rapid	Shallow
Soil avalanches	Translational sliding; subsidiary flow	Very high	X	X	X	X	Very rapid to extremely rapid	Shallow
Coherent slides								
Soil slumps	Sliding on basal shear surface; component of headward rotation	Slight or moderate	?	X	X	X	Slow to rapid	Deep
Soil block slides	Translational sliding on basal shear surface	Slight or moderate	?	?	X	X	Slow to very rapid	Deep

Slow earth flows	Translational sliding on basal shear surface; minor internal flow	Slight			X	X	Very slow to moderate with very rapid surges	Generally shallow occasionally deep
Lateral spreads and flows								
Soil lateral spreads	Translation on basal zone of liquefied gravel, sand, or silt or weakened, sensitive clay	Generally moderate; occasionally slight; occasionally high			X	X	Very rapid	Variable
Rapid soil flows	Flow	Very high	X	?	?	X	Very rapid to extremely rapid	Shallow
Subaqueous landslides	Complex, involving slumping, lateral spreading, and (or) flow	Generally high or very high; occasionally moderate			X	X	Rapid to extremely rapid	Deep

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[a] Slight: landslide consisting of one or a few coherent blocks. Moderate: landslide consisting of one or a few coherent blocks. High: landslide consisting of numerous small blocks and individual soil grains and rock fragments. Very high: landslide almost completely disaggregated into individual soil grains or small rock fragments.

[b] Extremely slow: less than 0.6 m/yr. Very slow: between 0.6 and 1.5 m/yr. Slow: between 1.5 m/yr and 1.5 m/mo. Moderate: between 1.5 m/mo and 1.5 m/d. Rapid: between 1.5 m/d and 0.3 m/min. Very rapid: between 0.3/min and 3 m/s. Extremely rapid: more than 3 m/s. Terminology from Varnes (1978).

[c] Shallow: generally less than 3 m. Deep: generally more than 3 m.

SOURCE: Wilson and Keefer (1985).

for applying to a wet season it is recommended that the MMI be increased by one unit. Yield acceleration has been used in conjunction with a Newmark (1965) analysis to prepare a regional map of seismically induced landslide susceptibility as a function of bedrock type, slope steepness, and seasonal groundwater-level conditions (Wieczorek et al., 1985).

Going a step further, ATC also used expert opinion to relate landslide severity (i.e., *SFS*) to the mean damage ratio (*MDR*) at affected facilities (see Table F-7). Thus, the mean damage ratio from landslides is:

$$MDR_{LS} = \sum_{SFS} P[SFS] \times CDF_{LS},$$

where $P[SFS]$ comes from Table F-6, the central damage factor CDF_{LS} is from Table F-7, and the products are summed over all slope stability states.

This ATC method is logically sound, but at this stage it involves considerable judgment and has not yet been tested for an actual large-scale study.

Mapping Landslide Hazards

During the Bay Area Project of the 1970s, a landslide hazard map was developed for the San Francisco Bay Area (Nilsen and Wright, 1979). The indicated hazardous areas were identified on the basis of evidence of past sliding (not necessarily during earthquakes) and topography.

Wieczorek et al. (1985) produced a map of earthquake-caused landslide susceptibility for one of the San Francisco Bay Area counties. In this approach, the nonseismic data needed are: maps showing the distribution of geologic materials; estimates of the wet and dry strength characteristics of each of the age or stratigraphic classifications obtained from the geologic maps; estimates of wet and dry season depths to saturated soil; and maps showing topography, with the contour intervals assigned to one of six percentage slope ranges.

These geologic-based susceptibility data are then combined with a consideration of ground motion. Faults capable of producing sufficient motion to cause slides are identified. (Because the map was intended to serve several purposes rather than being tied to a scenario-based disaster response planning study, the effects of the different earthquakes were not plotted discretely on the final map.) Several

TABLE F-6 Slope Failure Probability Matrices* (Summer Conditions)

SLOPE STABILITY: UNSTABLE, $a_c < .01$ g

SLOPE FAILURE STATE	MMI						
	VI	VII	VIII	IX	X	XI	XII
LIGHT	0	0	0	0	0	0	0
MODERATE	0	0	0	0	0	0	0
HEAVY	60	50	40	30	20	5	0
SEVERE	30	40	45	50	55	60	50
CATASTROPHIC	10	10	15	20	25	35	50
Σ_p	100%	100%	100%	100%	100%	100%	100%

SLOPE STABILITY: HIGH, 0.3 g $< a_c <$ 0.5 g

SLOPE FAILURE STATE	MMI						
	VI	VII	VIII	IX	X	XI	XII
LIGHT	100	100	100	95	85	80	60
MODERATE	0	0	0	5	10	15	20
HEAVY	0	0	0	0	5	5	15
SEVERE	0	0	0	0	0	0	5
CATASTROPHIC	0	0	0	0	0	0	0
Σ_p	100%	100%	100%	100%	100%	100%	100%

SLOPE STABILITY: LOW, .01 g $< a_c <$ 0.1 g

SLOPE FAILURE STATE	MMI						
	VI	VII	VIII	IX	X	XI	XII
LIGHT	40	25	15	10	5	0	0
MODERATE	30	30	35	30	20	10	0
HEAVY	25	35	40	40	35	35	30
SEVERE	5	10	10	15	30	35	40
CATASTROPHIC	0	0	0	5	10	20	30
Σ_p	100%	100%	100%	100%	100%	100%	100%

SLOPE STABILITY: STABLE, 0.5 g $< a_c <$ 0.7 g

SLOPE FAILURE STATE	MMI						
	VI	VII	VIII	IX	X	XI	XII
LIGHT	100	100	100	100	90	85	75
MODERATE	0	0	0	0	10	10	15
HEAVY	0	0	0	0	0	5	10
SEVERE	0	0	0	0	0	0	0
CATASTROPHIC	0	0	0	0	0	0	0
Σ_p	100%	100%	100%	100%	100%	100%	100%

TABLE F-6 (Continued)

SLOPE STABILITY: MODERATE, $0.1 \underline{g} < a_c\ 0.3 \underline{g}$

SLOPE FAILURE STATE	MMI						
	VI	VII	VIII	IX	X	XI	XII
LIGHT	100	100	85	70	55	20	0
MODERATE	0	0	10	20	25	30	10
HEAVY	0	0	5	10	15	25	40
SEVERE	0	0	0	0	5	15	30
CATASTROPHIC	0	0	0	0	0	10	20
Σ_p	100%	100%	100%	100%	100%	100%	100%

SLOPE STABILITY: VERY STABLE, $0.7 \underline{g} < a_c$

SLOPE FAILURE STATE	MMI						
	VI	VII	VIII	IX	X	XI	XII
LIGHT	100	100	100	100	100	90	80
MODERATE	0	0	0	0	0	10	15
HEAVY	0	0	0	0	0	0	5
SEVERE	0	0	0	0	0	0	0
CATASTROPHIC	0	0	0	0	0	0	0
Σ_p	100%	100%	100%	100%	100%	100%	100%

*Estimates are based on consensus of PEP and slope failure concept proposed by Legg et al. (1982), and are applicable for California summer season.

SLOPE FAILURE STATE SCALE

LIGHT - Insignificant ground movement, no apparent potential for landslide failure, ground shaking only effect. Predicted displacement less than 0.5 cm.

MODERATE - Moderate ground failure, small cracks likely to form, (having effects similar to lurch phenomena). Predicted displacement between 0.5 cm and 5.0 cm.

HEAVY - Major ground failure, moderate cracks and landslide displacements likely (having effects similar to liquefaction, lateral spread phenomena). Predicted displacement between 5.0 cm and 50 cm.

SEVERE - Extreme ground failure, large cracks and landslide displacements likely (having effects similar in severity to large-scale fault rupture). Predicted displacement between 50 cm and 500 cm.

CATASTROPHIC - Total failure, landslide moves large distances carrying everything with it. Predicted displacement greater than or equal to 500 cm.

SOURCE: Applied Technology Council (1985).

RELATIVE SEISMIC SLOPE STABILITY SCALE

V - Very stable: not likely to move under severe shaking, $a_c \geq 0.7 \underline{g}$

S - Stable: may undergo slight movement under severe shaking, $0.5 \underline{g} \leq a_c < 0.7 \underline{g}$

H - High: may undergo moderate movement under severe shaking; some landslides related to steep slopes, saturated conditions, and adverse dips, $0.3 \underline{g} \leq a_c < 0.5 \underline{g}$

M - Moderate: may undergo major movement under severe shaking or moderate movement under moderate shaking; numerous landslides, rock falls abundant, unconsolidated material undergoing deformation and failure, $0.1 \underline{g} \leq a_c < 0.1 \underline{g}$

L - Low: may undergo major movement under moderate shaking; abundant landslides of all types, $0.01 \underline{g} \leq a_c < 0.1 \underline{g}$

U - Unstable: may undergo major movement under slight shaking; most of area and/or materials falling, e.g., northern California coastal area, $a_c < 0.01 \underline{g}$

TABLE F-7 Relation Between Landslide Severity and Facility Damage Factor[a]

Central Slope Failure State	Damage Factor (percent)
Light	0
Moderate	15
Heavy	50
Severe	80
Catastrophic	100

[a] Estimates are based on consensus of the ATC-13 Project Engineering Panel.

SOURCE: Applied Technology Council (1985).

historic earthquake records are adapted to represent the size of earthquake assigned to each fault. Simple slope stability analysis is used to determine the yield or critical acceleration, a_c, necessary to overcome slope equilibrium.

The severity of the slide, in terms of the amount of displacement, is then computed using the method of Newman (1965) as adapted by Wilson and Keefer (1983), which accounts for the way in which successive accelerations of critical or greater size act over time, against the restraining influence of friction, to move the slide downhill.

The results are displayed on a map and divide the study area into high, moderate, low, and very low earthquake-caused landslide hazard zones. Liquefaction was beyond the scope of this method, but liquefaction susceptibility was also plotted on the same map from the work of Youd and Perkins (1985). The four descriptive landslide susceptibility categories are defined quantitatively in terms of predicted movement, relative to a benchmark amount of displacement of 5 cm (2 in.). This was considered a conservative estimate of the threshold of movement causing major damage to average building foundation conditions, based on Youd (1980). The other factor determining the assignment of a site into one of the four zones was the critical acceleration causing the movement.

For each of these four levels of susceptibility, an estimate is provided of the percentage of the area of that zone that would fail when the presumed earthquake occurs. This estimate of the extent of failure within each landslide zone is derived from Youd (1980).

Figure F-4 shows the maximum distance of several types of landslides as a function of magnitude and was assembled by Wilson and Keefer (1985) using data from California. These authors also used Newmark's sliding block theory to relate the likelihood of slides to the intensity of ground motions, and produced a map (see Figure F-5) giving the probability of coherent slides (in either hilly terrain or saturated soils) for a magnitude 6.5 earthquake on the Newport-Inglewood fault. This type of mapping is still in the developmental stage, and does depend heavily on historical data concerning earthquake-induced landslides. However, the work points the way to the type of analysis that can be used for mapping landslide hazards.

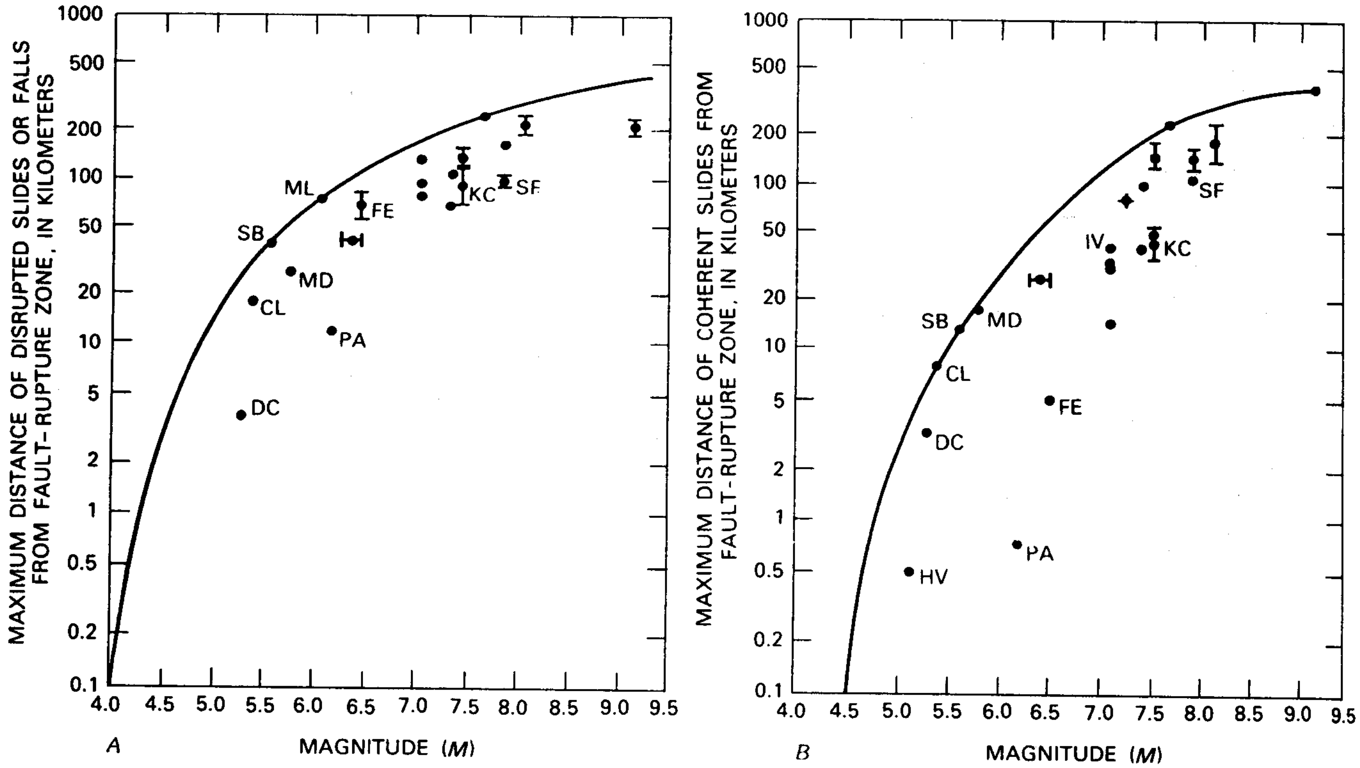

FIGURE F-4 Maximum distance from the fault-rupture zone (surface or subsurface) to landslides in earthquakes of different magnitudes (Keefer, 1984). California earthquakes in the data set as follows: CL, August 6, 1979, Coyote Lake; DC, March 22, 1957, Dale City: FE, February 9, 1971, San Fernando; HV, March 15, 1979, Homestead Valley; IV, May 19, 1940, Imperial Valley; KC, July 21, 1952, Kern County

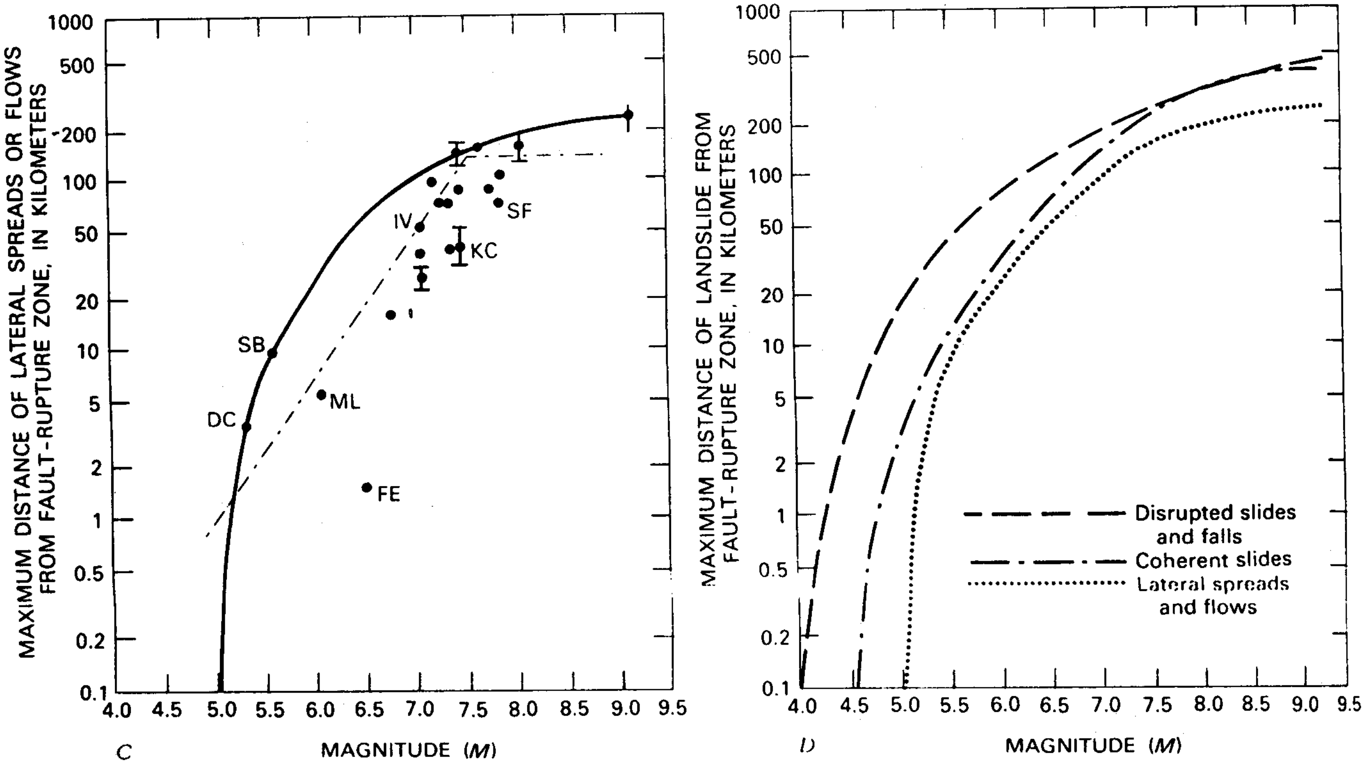

FIGURE F-4 (Continued) (not included by Keefer [1984]); MD, January 24, 1980, Greenville-Mount Diablo; ML, May 25, 1980, Mammoth Lakes; PA, June 28, 1966, Parkfield-Cholame; SB, August 13, 1978, Santa Barbara; SF, April 18, 1906, San Francisco. Unlabeled points represent earthquakes outside California (identified by Keefer [1984]). Source: Wilson and Keefer (1985).

FIGURE F-5 Map of the Los Angeles basin and surrounding uplands showing zones of probability for coherent landslides from a hypothetical M 6.5 earthquake on the northern Newport-Inglewood fault zone (straight line in center of map). The outer oval-shaped line is the limit for coherent slides from a M 6.5 earthquake based on worldwide data from historical earthquakes (Keefer, 1984). Most of the coherent landslides will occur within the 50 percent probability line. Source: Wilson and Keefer (1985).

Working Paper G
Economic Aspects of Earthquake Loss Estimation

The economic consequences of an earthquake are presented in most loss studies only as direct property losses, usually estimated as a percentage of replacement cost. While these estimates do provide some indication of the financial resources needed for reconstruction, another reason for often quoting direct losses in dollar terms is one of convenience. For planning, preparedness, and recovery purposes, one could just as easily use only estimates of the numbers and the types of structures with varying qualitative degrees of damage.

The study of natural hazards has long been dominated by engineers, sociologists, geographers, and social psychologists (Cochrane, 1984). Few economists have engaged in this field of study, leaving a large gap in knowledge of the overall economic accounting of the consequences of catastrophic earthquakes or other natural hazards. This does not mean, however, that these consequences are insignificant. Rather, it reflects the difficulties involved in conducting a comprehensive economic accounting of the effects of an earthquake.

The preceding working papers clearly demonstrate the complexities surrounding procedures for estimating direct earthquake losses. Efforts to estimate the indirect economic effects can complicate the study procedures significantly, particularly with respect to collecting additional information about structures and identifying the interrelationships among sectors in the economy and how they would change after the event. It is unlikely that these extended analyses will soon be incorporated into large-scale, general-purpose loss estimate studies. Interest in better understanding the economic consequences of earthquakes, however, led FEMA to sponsor an ambitious study, ATC-13 (Applied Technology Council, 1985), to lay the groundwork for estimating these impacts in a comprehensive fashion. This paper attempts to place a number of ATC-13's procedures in perspective, to discuss the current feasibility of doing such comprehensive economic analyses, and to outline briefly a research agenda that might enhance the feasibility of future studies.

CHARACTERIZING ECONOMIC LOSSES

The economic consequences of an earthquake can be classified in several ways, but for purposes here, three types are delineated: (1) direct losses due to damage; (2) losses due to premature death or injury, and (3) indirect losses due to business disruption. Estimates of the direct property losses follow in a straightforward fashion from damage estimates, but the other two types of losses warrant some further discussion.

As a first approximation to losses from premature mortality, Sorkin (1982) suggests multiplying the expected number of deaths by the present value of expected future earnings foregone, considering the likely age, sex, and occupational profiles of the victims and their effects on expected future earnings. The indirect costs of injuries are reflected in foregone earnings and medical costs. In extremely severe earthquake events, these economic losses could be substantial and certainly tragic for the victims' families. Estimates of this kind may also be important for insurance purposes or other questions of legal liability. However, the majority of these losses are in the form of foregone future earnings, rather than immediate out-of-pocket costs.

For this reason, in addition to the tremendous uncertainties surrounding casualty estimates, these losses should not be a major focus of economic loss studies. The public concern should be with the casualties themselves and efforts to reduce them, rather than foregone future earnings.

However, the same conclusion cannot be applied to indirect business losses stemming from physical damage and disruptions due to the earthquake. These indirect losses are immediate and can persist throughout the recovery effort. They can affect the entire region and spill over to other states and regions of the country. For a variety of reasons, ranging from hazard mitigation and recovery to concerns about national security and increased vulnerability after the event, these indirect losses are potentially of major concern to the local economy and to the federal government.

MEASURING INDIRECT ECONOMIC IMPACTS

FEMA's ambitious study to identify in a comprehensive fashion the economic consequences of a catastrophic earthquake has two major components. The first, ATC-13, involves a damage estimation technique that integrates geocoded seismic intensity simulations and inventories of buildings and other facilities with damage functions, relating seismic intensity and construction characteristics to damage estimates. The second component is designed to determine the overall economic impact by using the results from the damage evaluation methodology in conjunction with recently developed economic interindustry modeling capacities.

ATC-13 describes only the first component of FEMA's study design. Its loss estimates are confined to the direct effects of the earthquake (e.g., damage from ground motion and collateral hazards) along with estimates of casualties, property loss (measured as a percentage of replacement cost), and loss of function. From this standpoint, its objectives are not that much different from those of other studies or approaches.

However, the procedures by which estimates of these losses are produced differ significantly from what others have done. One major difference is the level of detail attempted in terms of the number of construction classes and the classification of economic and social function. The attempt to add detail to the damage relationships by consulting a number of experts was unique, as was the attempt to generate a comprehensive inventory from socioeconomic data in automated form available from FEMA. The rationale for the inventory procedures was in part due to a desire for consistency in studies throughout the country.

Shortcomings of FEMA's methodology stem from the large number of construction and use classifications and the fact that the iterative process used with the experts led to distributions that may underestimate the true variability in damages. The accuracy of inferring structural information from the social and economic functions of buildings is questionable and has not been empirically verified.

In terms of the damage relationships, it is probably true that little would be lost by considering a smaller number of separate damage curves or matrices. If this were done and the estimates were not revised through this iterative process, the damage relationships would probably not be too much different from those used in other studies. The real shortcoming of the method is in having to relate economic and social function to structure type at such a disaggregate level—at the level of each individual building or other facility.

One way that the procedures could be improved is to invest more time and money in collecting more detailed information about the use of structures in the inventory. An alternative might be to conduct some general field research to determine if there is any systematic relationship concerning economic function, geographic location, and age and type of structure.

Why was such a high level of disaggregation needed in the ATC-13 study? The answer derives from FEMA's interest (or that of the National Security Council, which requested the study) in identifying the impact of an earthquake on any one of up to 470 economic sectors identified by the Standard Industrial Classification (SIC) code used by the Bureau of Economic Analysis (Executive Office of the President, 1972). This motivation is probably related more to the national security implications of loss of function to specific defense or related high-technology industries than it is to education, mitigation, and planning efforts.

If the first phase of the ATC-13 methodology could be implemented at this level of detail, then some initial estimates of loss of function to defense related or other "critical" industries might be possible. However, these direct damage and loss estimates ignore important secondary effects throughout the economy after catastrophic events. (This is true regardless of the level of disaggregation in the analysis.)

These secondary impacts are due to a variety of things. Probably most important is the loss of productive capacity from damage to physical plant and equipment. This reduces the capacity of the economic sectors to produce goods for final consumption as well as for use as intermediate inputs (some of which might have strategic value) in other productive activities. Because of the damage to the area's productive capacity, a larger fraction of the area's continuing demands for goods and services need to be imported from other regions of the country, at least during the recovery period.

Employment and income in those sectors damaged by the event are reduced also, and this in turn reduces the demand for goods and services in many of the region's economic sectors. However, recovery activities bring with them an influx of financial resources (e.g., from government recovery and relief efforts, and insurance claims) that increases the demand for the output of certain sectors, particularly construction. These new demands are either met by the remaining productive capacity of the area or through interregional imports.

The purpose of the second phase of FEMA's study is to attempt estimates of these secondary impacts at the four-digit SIC level. In theory, this is possible by using an interregional interindustry model of the U.S. economy. The most complete description of the model intended for use in conjunction with ATC-13 is in a paper by Wilson (1982).

The methods to be used in this phase of FEMA's study can be described in abbreviated fashion through simple equations. The basic interindustry, input-output (I-O) model developed initially by Leontief (1951) is described in numerous economic books and in a summary by Wilson (1982). The model is developed essentially from a double-entry bookkeeping description of an area's economy that records purchases and sales of goods from one sector to another, as well as imports and sales to final users (e.g., to final demand).

Total sales or output of any sector (e.g., agriculture, manufacturing, and services) of an n-sector model are recorded along the rows of the transactions table and are expressed as

$$\sum_{j=1}^{n} x_{ij} + y_i = x_i (i = 1, \ldots, n), \qquad (1)$$

where x_{ij} is the value of the output of sector i purchased by sector j, y_i is the final demand for the output of sector i, and x_i is the value of the total output of sector i.

To complete this set of balance equations, the entries down the columns of the table also add to the value of a sector's output.

$$\sum_{i=1}^{n} x_{ij} + p_j = x_j (j = 1, \ldots, n), \qquad (2)$$

where p_j is the final payments (purchases of imports and primary factors of production by sector j), x_j is total outlay (purchases) of sector j, and x_i equals x_j for all $i = j$.

From this transactions table, a matrix, A, of direct input requirements from sector i (in dollars) per dollar of sector j's output is given by

$$A = a_{ij} = \left\{ \frac{x_{ij}}{x_j} \right\} (i, j = 1, \ldots, n). \tag{3}$$

Substituting (4) into (1) yields

$$x_i = \sum_{j=1}^{n} a_{ij} x_j + y_i (i = 1, \ldots, n), \tag{4}$$

which may be expressed more compactly as

$$X = AX + Y, \tag{5}$$

where

$$X = \begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_n \end{bmatrix}, \ A = \begin{bmatrix} a_{11} & a_{12} & \ldots & a_{1n} \\ a_{21} & a_{22} & \ldots & a_{2n} \\ \vdots & & & \vdots \\ a_{n1} & a_{n2} & \ldots & a_{nn} \end{bmatrix}, \ and\ Y = \begin{bmatrix} y_1 \\ \vdots \\ y_n \end{bmatrix}. \tag{6}$$

Rearranging this set of equations, it is easy to see that gross output minus intermediate use equals the net output or final use of the system

$$X - AX = (I - A)X = Y. \tag{7}$$

In the economics literature, much of the policy analysis that uses interindustry models is focused on the fact that this set of equations can be used to estimate the total output in the economic system required to meet any given set of final exogenous demands (e.g., consumer demand, government purchases, and exports). That is, if one knows the specific values for the components of Y, one can solve for required output by

$$X = (I - A)^{-1} Y. \tag{8}$$

In the planned second phase of the economic study, FEMA would make use of the direct damages and loss estimates coming out of the ATC-13 method. The first task would be to estimate the interindustry model for the geographic area of interest (e.g., estimate the predisaster A matrix). Historically, this has been done either through extensive questioning of a sample of local businesses (Bills and Barr, 1968), or through systematic adjustments to the national interindustry table based on some measure of the region's economic activity in a particular sector to that of the nation (Boisvert and Bills, 1976; Hwang and Maki, 1979; Lofting and Davis, 1973).

To estimate economic losses from natural hazards, these nonsurvey techniques are the only feasible approach, and FEMA chose to use the procedures developed by Lofting and Davis (1973), which are based on a biproportional matrix-balancing technique (RAS) developed by Stone (referred to in Wilson, 1982 and Boisvert and Bills, 1976). The procedures by Lofting and Davis, and Hwang and Maki, accommodate the development of integrated interindustry models that account directly for trade flows across more than one region and can trace the impact to other regions in the country. Wilson (1982) discusses this extension of the model.

Once the interindustry model is in place, on the basis of the initial direct loss estimates, procedures would be developed to estimate new levels of final demand, Y, in the postdisaster situation. This would require establishing estimates of the loss in income due to the event and the projected influx of resources due to recovery efforts, as well as estimates of how these changes affect final demand for each sector's output. Projecting changes in final demand as a result of disruptions in an economy (be they due to economic or other factors) is not an easy task, but it is something that is done frequently in interindustry studies.

The third task would be to modify the interindustry tables for the region. That is, in most interindustry studies, it is assumed that the intermediate input requirements, the A matrix, is invariant to the initial change in economic activity. This, of course, could not be assumed after an earthquake because of the damage to plant and equipment and the corresponding reduction in productive capacity. In general, this would mean that many of the components of the matrix A would be reduced—indicating that more of a sector's intermediate input requirements from other sectors would be imported from outside the region. There has been very little, if any, work attempting to modify interindustry models to account for an immediate structural change in intermediate input flows caused by a major disaster.

SUMMARY AND CONCLUSION

Little comprehensive analysis of the overall economic impact of earthquakes on a regional economy exists but an economist's general knowledge of a region's interindustry relations would suggest that the secondary (or indirect) effects stemming from the initial damage are likely to be substantial. It would be useful to link our estimates of damage to buildings and other facilities with their economic function. This information could assist recovery by helping to set priorities for reconstruction of essential services and perhaps to identify the location of industries that use toxic or other hazardous substances that could be released during the earthquake.

The key question is, however, At what cost? Data to implement the procedures do not exist, and if the inventory of facilities had to include data on economic function, the costs of this phase would increase substantially (by as much as 40 percent by one estimate). Furthermore, even if there were reliable estimates of direct losses to structures by economic function, serious problems remain in trying to relate direct losses to changes in final demand and other interindustry relationships. These difficulties can only be resolved through additional research.

Regardless of how rapidly some of the research problems are resolved, it is unlikely that comprehensive economic analysis will be viewed in the near future as an integral part of what has been called Type I studies (general purpose, large scale) in Working Paper A. This does not mean that the procedures used in future loss estimation studies should be insensitive to the data requirements of more complete economic analysis of the consequences of catastrophic earthquakes. At a minimum, researchers should collect inventory information that relates construction class to economic and social function or undertake specific research to establish any systematic relationships that might exist.

Furthermore, to be useful for hazard reduction, emergency planning, and recovery planning efforts, the level of detail in terms of economic and social function does not need to be fine enough to differentiate all 470 sectors. A reasonable objective would be to look initially at the 25 to 30 major economic classifications defined by the SIC, with the expectation that there might be a handful of important individual industries in any region that could be examined in greater detail. These would depend on the location being studied and the purpose of the study. Major defense contractor plants and military bases could be studied in greater detail if the purpose is defense-related, as in the case of ATC-13.

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1990-720-220/10968