# Chapter 8
# Direct Damage to Lifelines - Utility Systems

This chapter describes and presents the methodology for estimating direct damage to Utility Systems. The Utility Module is composed of the following six systems:

- Potable Water
- Waste Water
- Oil (crude and refined)
- Natural Gas
- Electric Power
- Communication

The flowchart of the overall methodology, highlighting the utility system module and its relationship to other modules, is shown in Flowchart 8.1.

## 8.1 Potable Water Systems

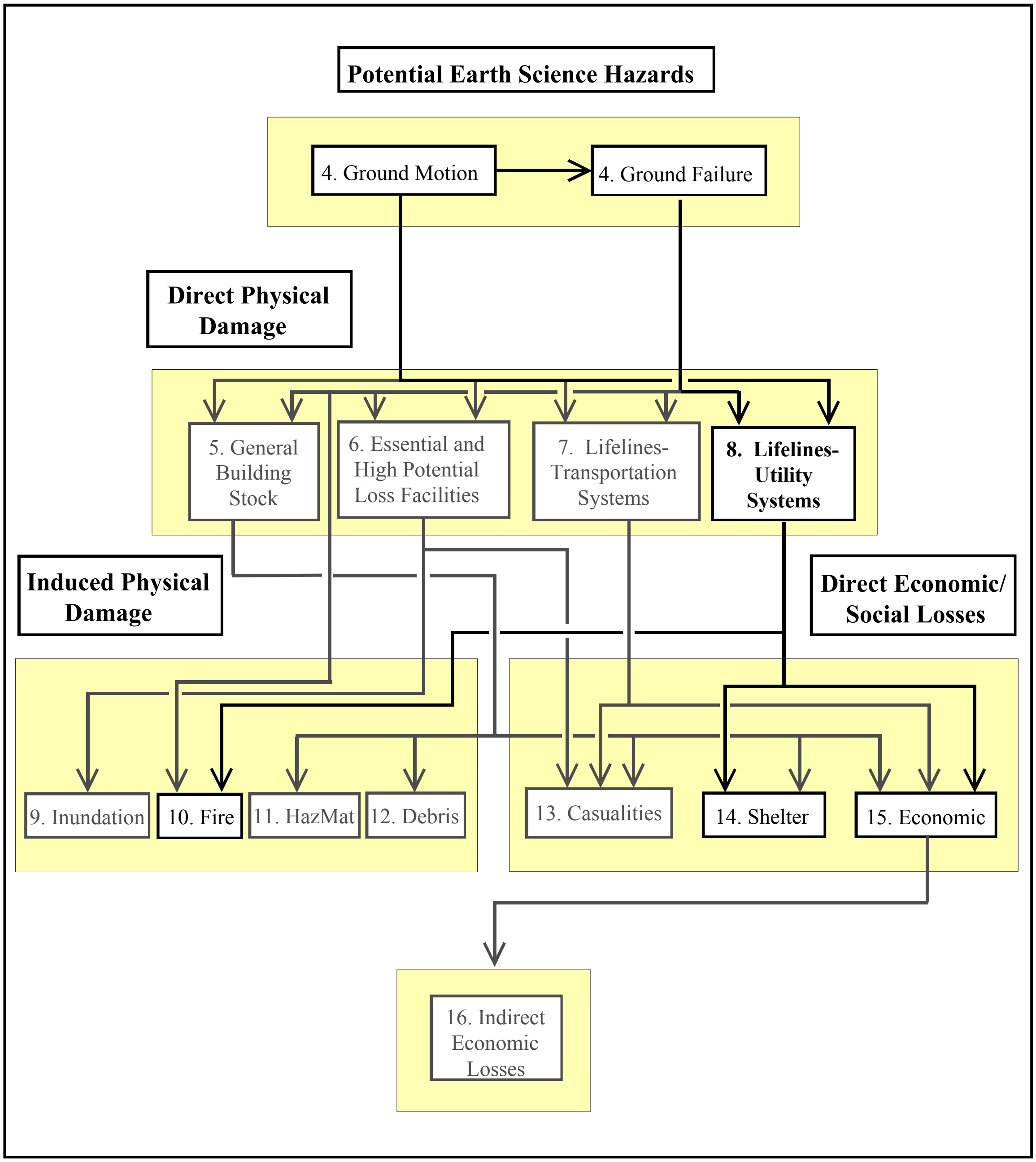
### 8.1.1 Introduction

This section presents a loss estimation methodology for a water system during earthquakes. This system consists of supply, storage, transmission, and distribution components. All of these components are vulnerable to damage during earthquakes, which may result in a significant disrutpion to the water utility network.

### 8.1.2 Scope

The scope of this section includes development of methods for estimation of earthquake damage to a potable water system given knowledge of the system's components (i.e., tanks, aqueducts, water treatment plants, wells, pumping stations, conveyance pipes, junctions, hydrants, and valves), classification (i.e., for water treatment plants, small, medium or large), and the ground motion (i.e. peak ground velocity, peak ground acceleration and/or permanent ground deformation). Damage states describing the level of damage to each of the water system components are defined (i.e., slight/minor, moderate, extensive, or complete), while for pipelines, the number of repairs/km is the key paramter. Fragility curves are developed for each classification of the water system component. These curves describe the probability of reaching or exceeding each damage state given the level of ground motion or ground failure.

Based on these fragility curves, a method for assessing functionality of each component of the water system is presented. A simplified approach for evaluating the overall water system network performance is also provided.




**Flowchart 8.1 Utility System Damage Relationship to Other Modules of the Earthquake Loss Estimation Methodology**

### 8.1.3 Input Requirements and Output Information

Depending on the desired level of analysis, the input required for analyzing water systems varies. In total, three levels of analysis are enabled in HAZUS.

***Level One:***
The default inventory in HAZUS contains estimate of potable water pipelines aggregated at the census tract level. This pipeline data was developed using the US Census TIGER street file datasets. For the level one analysis, eighty (80) percent of the pipes are assumed to be brittle with the remaining pipes assumed to be ductile. In addition, peak ground velocity and permanent ground deformation (PGV and PGD) for each census tract is needed for the analysis.

The results from a level one analysis include the expected number of leaks and breaks per census tract and a simplified evaluation of the potable water system network performance (i.e. number of households without water).

***Level Two:***
For this level, the input required to estimate damage to potable water systems includes the following items:

**Transmission Aqueducts and Distribution Pipelines**

- Geographical location of aqueduct/pipe links (longitude and latitude of end nodes)
- Peak ground velocity and permanent ground deformation (PGV and PGD)
- Classification (ductile pipe or brittle pipe)

**Reservoirs, Water Treatment Plants, Wells, Pumping Stations and Storage Tanks**

- Geographical location of facility (longitude and latitude)
- PGA and PGD
- Classification (e.g., capacity and anchorage)

Direct damage output from level 2 analysis includes probability estimates of (1) component functionality and (2) damage, expressed in terms of the component's damage ratio (repair cost to replacement cost). Note that damage ratios for each of the potable water system components are presented in section 15.3 of Chapter 15. In addition, a simplified evaluation of the potable water system network performance is also provided. This is based on network analyses done for Oakland, San Francisco and Tokyo. The output from this simplified version of network analysis consists of an estimate of the flow reduction to the areas served by the water system being evaluated. Details of this methodology are presented in subsection 8.1.9.

***Level Two Enhanced:***

This level of analysis essentially relies on the same type of information provided in the previous level with four main differences:

- Three additional components are considered.  These are: junctions, hydrants, and valves.
- Connectivity of the components is maintained (i.e., what facilities are connected to which pipeline links or valves).
- Serviceability in the system considered (i.e., the demand pressures and flow demands at the different distribution nodes).
- Input data for the water system need to be in one of the following three commercially available formats: KYPIPE, EPANET, or CYBERNET.

Recent work by Khater and Waisman (EQE, 1999) elaborates in great details on the level two enhanced analysis model implemented in **HAZUS®**.  In particular, this work provides a comprehensive theoretical background on the governing equations for a water system and explains how the commercial data need to be formatted in order to be able to import it into **HAZUS®**.  This work is available in a separate document entitled "Potable Water System Analysis Model (POWSAM)" that can be acquired directly from NIBS.

Results from the level two enhanced analysis are similar to the level two.  That is, probability estimates of (1) component functionality and (2) damage, expressed in terms of the component's damage ratio (repair cost to replacement cost).  The main difference is in the evaluation of the potable water system network performance, which is in this case based on a more comprehensive approach.  Note that in either case, the performance is expressed in terms of an estimate of the flow reduction to the areas served by the water system being evaluated and the number of households expected to be deprived from water.

### 8.1.4 Form of Damage Functions

Damage functions or fragility curves for water system components other than pipelines are modeled as lognormally-distributed functions that give the probability of reaching or exceeding different damage states for a given level of ground motion (quantified in terms of PGA) and ground failure (quantified in terms of PGD).  Each of these fragility curves is characterized by a median value of ground motion (or failure) and an associated dispersion factor (lognormal standard deviation).  For pipelines, empirical relations that give the expected repair rates due to ground motion (quantified in terms of PGV) or ground failure (quantified in terms of PGD) are provided.  Definitions of various damage states and the methodology used in deriving all these fragility curves are presented in the next section.

### 8.1.5 Description of Potable Water System Components

A potable water system typically consists of terminal reservoirs, water treatment plants, wells, pumping plants, storage tanks and transmision and distribution pipelines. In this subsection, a brief description of each of these components is presented.

**Terminal Reservoirs**

Terminal reservoirs are typically lakes (man made or natural) and are usually located nearby and upstream of the water treatment plant. Vulnerability of terminal reservoirs and associated dams is marginally assessed in the loss estimation methodology. Therefore, even though reservoirs are an essential part of a potable water system, it is assumed in the analysis of water systems that the amount of water flowing into water treatment plants from reservoirs right after an earthquake is essentially the same as before the earthquake.

**Transmission Aqueducts**

These transmission conduits are typically large size pipes (more than 20 inches in diameter) or channels (canals) that convey water from its source (reservoirs, lakes, rivers) to the treatment plant.

Transmission pipelines are commonly made of concrete, ductile iron, cast iron, or steel. These could be elevated/at grade or buried. Elevated or at grade pipes are typically made of steel (welded or riveted), and they can run in single or multiple lines.

Canals are typically lined with concrete, mainly to avoid excessive loss of water by seepage and to control erosion. In addition to concrete lining, expansion joints are usually used to account for swelling and shrinkage under varying temperature and moisture conditions. Damageability of channels has occurred in some earthquake, but is outside the scope of the scope of the methodology.

**Supply Facilities- Water Treatment Plants (WTP)**

Water treatment plants are generally composed of a number of physical and chemical unit processes connected in series, for the purpose of improving the water quality. A conventional WTP consists of a coagulation process, followed by a sedimentation process, and finally a filtration process. Alternately, a WTP can be regarded as a system of interconnected pipes, basins, and channels through which the water moves, and where the flow is governed by hydraulic principles. WTP are categorized as follows:

Small water treatment plants, with capacity ranging from 10 mgd to 50 mgd, are assumed to consist of a filter gallery with flocculation tanks (composed of paddles and baffles) and settling (or sedimentation) basins as main components, chemical tanks (needed in the coagulation and other destabilization processes), chlorination tanks, electrical and mechanical equipment, and elevated pipes.

Medium water treatment plants, with capacity ranging from 50 mgd to 200 mgd, are simulated by adding more redundancy to small treatment plants (i.e. twice as many flocculation, sedimentation, chemical and chlorination tanks).

Large water treatment plants, with capacity above 200 mgd, are simulated by adding even more redundancy to small treatment plants (i.e., three times as many flocculation, sedimentation, chemical and chlorination tanks/basins).

Water treatment plants are also classified based on whether the subcomponents (equipment and backup power) are anchored or not as defined in section 7.2.5.

**Pumping Plants (PP)**

Pumping plants are usually composed of a building, one or more pumps, electrical equipment, and in some cases, backup power systems. Pumping plants are classified as either small PP (less than 10 mgd capacity) or medium/large PP (more than 10 mgd capacity). Pumping plants are also classified with respect to whether the subcomponents (equipment and backup power) are anchored or not. As noted in Chapter 7, anchored means equipment designed with special seismic tie downs and tiebacks while unanchored means equipment with manufactures normal requirements.

**Wells (WE)**

Wells typically have a capacity between 1 and 5 mgd. Wells are used in many cities as a primary or supplementary source of water supply. Wells include a shaft from the surface down to the aquifer, a pump to bring the water up to the surface, equipment used to treat the water, and sometimes a building, which encloses the well and equipment.

**Water Storage Tanks (ST)**

Water storage tanks can be elevated steel, on ground steel (anchored/unanchored), on ground concrete (anchored/unanchored), buried concrete, or on ground wood tanks. Typical capacity of storage tanks is in the range of 0.5 mgd to 2 mgd.

**Distribution Facilities and Distribution Pipes**

Distribution of water can be accomplished by gravity, or by pumps in conjunction with on-line storage. Except for storage reservoirs located at a much higher altitude than the area being served, distribution of water would necessitate, at least, some pumping along the way. Typically, water is pumped at a relatively constant rate, with flow in excess of consumption being stored in elevated storage tanks. The stored water provides a reserve for fire flow and may be used for general-purpose flow should the electric power fail, or in case of pumping capacity loss.

Distribution pipelines are commonly made of concrete (prestressed or reinforced), asbestos cement, ductile iron, cast iron, steel, or plastic. The selection of material type and pipe size are based on the desired carrying capacity, availability of material, durability, and cost. Distribution pipes represent the network that delivers water to consumption areas. Distribution pipes may be further subdivided into primary lines, secondary lines, and small distribution mains. The primary or arterial mains carry flow from the pumping station to and from elevated storage tanks, and to the consumption areas, whether residential, industrial, commercial, or public. These lines are typically laid out in interlocking loops, and all smaller lines connecting to them are typically valved so that failure in smaller lines does not require shutting off the larger. Primary lines can be up to 36 inches in diameter. Secondary lines are smaller loops within the primary mains and run from one primary line to another. They serve primarily to provide a large amount of water for fire fighting without excessive pressure loss. Small distribution lines represent the mains that supply water to the user and to the fire hydrants.

In this earthquake loss estimation study, the simplified method for water system network performance evaluation applies to a distribution pipe network digitized at the primary level.

### 8.1.6 Definition of Damage States

Potable water systems are susceptible to earthquake damage. Facilities such as water treatment plants; wells, pumping plants and storage tanks are most vulnerable to PGA, and sometimes PGD, if located in liquefiable or landslide zones. Therefore, the damage states for these components are defined and associated with PGA and PGD. Aqueducts and pipelines, on the other hand, are vulnerable to PGV and PGD. Therefore, the damage states for these components are associated with these two ground motion parameters.

#### 8.1.6.1 Damage State Defintions for Components Other than Pipelines

A total of five damage states for potable water system components are defined. These are none ($ds_1$), slight/minor ($ds_2$), moderate ($ds_3$), extensive ($ds_4$), and complete ($ds_5$).

**<u>Slight/Minor Damage</u> ($ds_2$)**

- **<u>For water treatment plants</u>**, $ds_2$ is defined by malfunction of plant for a short time (less than three days) due to loss of electric power and backup power if any, considerable damage to various equipment, light damage to sedimentation basins, light damage to chlorination tanks, or light damage to chemical tanks.  Loss of water quality may occur.

- **<u>For pumping plants</u>**, $ds_2$ is defined by malfunction of plant for a short time (less than three days) due to loss of electric power and backup power if any, or slight damage to buidings.

- **<u>For wells</u>**, $ds_2$ is defined by malfunction of well pump and motor for a short time (less than three days) due to loss of electric power and backup power if any, or light damage to buidings.

- **<u>For Storage Tanks</u>**, $ds_2$ is defined by the tank suffering minor damage without loss of its contents or functionality.  Minor damage to the tank roof due to water sloshing, minor cracks in concrete tanks, or localized wrinkles in steel tanks fits the description of this damage state.

**<u>Moderate Damage</u> ($ds_3$)**

- **<u>For water treatment plants</u>**, $ds_3$ is defined by malfunction of plant for about a week due to loss of electric power and backup power if any, extensive damage to various equipment, considerable damage to sedimentation basins, considerable damage to chlorination tanks with no loss of contents, or considerable damage to chemical tanks. Loss of water quality is imminent.

- **<u>For pumping plants</u>**, $ds_3$ is defined by the loss of electric power for about a week, considerable damage to mechanical and electrical equipment, or moderate damage to buildings.

- **<u>For wells</u>**, $ds_3$ is defined by malfunction of well pump and motor for about a week due to loss of electric power and backup power if any, considerable damage to mechanical and electrical equipment, or moderate damage to buildings.

- **<u>For Storage Tanks</u>**, $ds_3$ is defined by the tank being considerably damaged, but only minor loss of content.  Elephant foot buckling for steel tanks without loss of content, or moderate cracking of concrete tanks with minor loss of content fits the description of this damage state.

**Extensive Damage ($ds_4$)**

- **For water treatment plants**, $ds_4$ is defined by the pipes connecting the different basins and chemical units being extensively damaged.  This type of damage will likely result in the shutdown of the plant.

- **For pumping plants**, $ds_4$ is defined by the building being extensively damaged, or the pumps being badly damaged beyond repair.

- **For wells**, $ds_4$ is defined by the building being extensively damaged or the well pump and vertical shaft being badly distorted and nonfunctional.

- **For Storage Tanks**, $ds_4$ is defined by the tank being severely damaged and going out of service.  Elephant foot buckling for steel tanks with loss of content, stretching of bars for wood tanks, or shearing of wall for concrete tanks fits the description of this damage state.

**Complete Damage ($ds_5$)**

- **For water treatment plants**, $ds_5$ is defined by the complete failure of all pipings, or extensive damage to the filter gallery.

- **For pumping plants**, $ds_5$ is defined by the building collapsing.

- **For wells**, $ds_5$ is defined by the building collapsing.

- **For Storage Tanks**, $ds_5$ is defined by the tank collapsing and losing all of its content.

### 8.1.6.2 Defintion of Damage States for Pipelines

For pipelines, two damage states are considered.  These are leaks and breaks.  Generally, when a pipe is damaged due to ground failure (PGD), the type of damage is likely to be a break, while when a pipe is damaged due to seismic wave propagation (PGV), the type of damage is likely to be joint pull-out or crushing at the bell.  In the loss methodology, it is assumed that damage due to seismic waves will consist of 80% leaks and 20% breaks, while damage due to ground failure will consist of 20% leaks and 80% breaks.  The user can override these default percentages.

## 8.1.7 Component Restoration Curves

Restoration functions for potable water system components, namely, water treatment plants, wells, pumping plants, and storage tanks are based on SF-30a, SF-30b and SF-30d of ATC-13 consistent with damage states defined in the previous section.  That is, restoration functions for $ds_2$, $ds_3$, $ds_4$, and $ds_5$ defined herein are assumed to correspond to $ds_2$, $ds_3$, $ds_4$, and $ds_5$ of ATC-13. The parameters of these restoration curves are given in Tables 8.1.a and 8.1.b, and 8.1.c.

**Table 8.1.a: Continuous Restoration Functions for Potable Water Systems (After ATC-13, 1985)**

| Restoration Functions (All Normal Distributions) | | | |
|---|---|---|---|
| **Classification** | **Damage State** | **Mean (Days)** | **σ (days)** |
| Water Treatment Plants | slight/minor | 0.9 | 0.3 |
| | moderate | 1.9 | 1.2 |
| | extensive | 32.0 | 31.0 |
| | complete | 95.0 | 65.0 |
| Pumping Plants | slight/minor | 0.9 | 0.3 |
| | moderate | 3.1 | 2.7 |
| | extensive | 13.5 | 10.0 |
| | complete | 35.0 | 18.0 |
| Wells | slight/minor | 0.8 | 0.2 |
| | moderate | 1.5 | 1.2 |
| | extensive | 10.5 | 7.5 |
| | complete | 26.0 | 14.0 |
| Water Storage Tanks | slight/minor | 1.2 | 0.4 |
| | moderate | 3.1 | 2.7 |
| | extensive | 93.0 | 85.0 |
| | complete | 155.0 | 120.0 |

Table 8.1.a gives means and standard deviations for each restoration curve (i.e., smooth continuous curve), while Table 8.1.b gives approximate discrete functions for the restoration curves developed. These restoration functions are also shown in Figures 8.1 through 8.4.

**Table 8.1.b: Discretized Restoration Functions for Potable Water System Components**

| Discretized Restoration Functions | | | | | | |
|---|---|---|---|---|---|---|
| **Classification** | **Damage State** | **1 day** | **3 days** | **7 days** | **30 days** | **90 days** |
| Water Treatment Plants | slight/minor | 65 | 100 | 100 | 100 | 100 |
| | moderate | 23 | 82 | 100 | 100 | 100 |
| | extensive | 16 | 18 | 21 | 48 | 97 |
| | complete | 7 | 8 | 9 | 16 | 47 |
| Pumping Plants | slight/minor | 65 | 100 | 100 | 100 | 100 |
| | moderate | 22 | 50 | 93 | 100 | 100 |
| | extensive | 10 | 15 | 25 | 95 | 100 |
| | complete | 3 | 4 | 6 | 40 | 100 |

**Table 8.1.b: Discretized Restoration Functions for Potable Water System Components (continued)**

| Discretized Restoration Functions | | | | | | |
|---|---|---|---|---|---|---|
| **Classification** | **Damage State** | **1 day** | **3 days** | **7 days** | **30 days** | **90 days** |
| Wells | slight/minor | 85 | 100 | 100 | 100 | 100 |
| | moderate | 34 | 90 | 100 | 100 | 100 |
| | extensive | 11 | 16 | 33 | 100 | 100 |
| | complete | 4 | 6 | 9 | 62 | 100 |
| Water Storage Tanks | slight/minor | 30 | 100 | 100 | 100 | 100 |
| | moderate | 20 | 49 | 93 | 100 | 100 |
| | extensive | 13 | 15 | 16 | 23 | 49 |
| | complete | 10 | 11 | 12 | 15 | 30 |

The restoration functions for pipelines are expressed in terms of number of days needed to fix the leaks and breaks. These restoration functions are given in Table 8.1.c

**Table 8.1.c: Restoration Functions for Potable Water Pipelines**

| Class | Diameter from: [in] | Diameter to: [in] | # Fixed Breaks per Day per Worker | # Fixed Leaks per Day per Worker | # Available Workers | Priority |
|---|---|---|---|---|---|---|
| a | 60 | 300 | 0.33 | 0.66 | 20% of Total | 1 (Highest) |
| b | 36 | 60 | 0.33 | 0.66 | 20% of Total | 2 |
| c | 20 | 36 | 0.33 | 0.66 | 20% of Total | 3 |
| d | 12 | 20 | 0.50 | 1.0 | 15% of Total | 4 |
| e | 8 | 12 | 0.50 | 1.0 | 15% of Total | 5 (Lowest) |
| u | Unknown diameter | or for Default Data Analysis | 0.50 | 1.0 | 10% of Total | 6 (lowest) |
| | | | | Total | 0.02% x (#P) | |

Where the total number of available workers is estimated as [0.02%] x {Total number of People in Study Region}. It should be noted that the values in Table 8.1.c are based on the following 4 assumptions:

(1) "Pipes that are less than 20" in diameter are defined as small, while pipes with diameter greater than 20" are defined as large."
(2) For both small and large pipes a 16 hour day shift is assumed.

(3) For small pipes, a 4-person crew needs 4 hours to fix a leak, while the same 4-person crew needs 8 hours to fix a break. (Mathematically, this is equivalent to saying it takes 16 people to fix a leak in one hour and it takes 32 people to fix a break in one hour).
(4) For large pipes, a 4-person crew needs 6 hours to fix a leak, while the same 4-person crew needs 12 hours to fix a break. (Mathematically, this is equivalent to say it takes 24 people to fix a leak in one hour and 48 people to fix a break in one hour).
With this algorithm for potable water pipelines, the total number of days needed to finish repairs is calculated as:

Days needed to finish all repairs = (1/available work) * [(# small pipe leaks/1.0) + (# small pipe breaks/0.5) +(# large pipe leaks/0.66) + (# large pipe breaks/0.33)]

The percentage of repairs finished at Day1, Day3, Day7, Day30, and Day90 are then computed using linear interpolation.

### 8.1.8 Development of Damage Functions

In this subsection, damage functions for the various components of a potable water system are presented. In cases where the components are made of subcomponents (i.e., water treatment plants, pumping plants, and wells), fragility curves for these components are based on the probabilistic combination of subcomponent damage functions using Boolean expressions to describe the relationship of subcomponents to the components. It should be mentioned that the Boolean logic is implicitly presented within the definition of a particular damage state. For example, slight/minor damage for a water treatment plant was defined by malfunction for a short time due to loss of electric power AND backup power (if any), considerable damage to various equipment, light damage to sedimentation basins, light damage to chlorination tanks, OR light damage to chemical tanks. Therefore, the fault tree for slight/minor damage has FIVE primary OR branches: electric power, equipment, sedimentation basins, chlorination tanks, and chemical tanks, and TWO secondary AND branches under electric power: commercial power and backup power. The Boolean approach involves evaluation of the probability of each component reaching or exceeding different damage states, as defined by the damage level of its subcomponents. These evaluations produce component probabilities at various levels of ground motion. In general, the Boolean combinations do not produce a lognormal distribution, so a lognormal curve that best fits this probability distribution is determined numerically. It should be mentioned that damage functions due to ground failure (i.e., PGD) for all potable water systems components except pipelines (i.e., water treatment plants, pumping plants, wells, and storage tanks) are assumed to be similar to those described for buildings, unless specified otherwise. These are:

- For lateral spreading, a lognormal damage function with a median of 60 inches and a dispersion of 1.2 is assumed for the damage state of "at least extensive". 20% of this damage is assumed to be complete. For a PGD of 10 inches due to lateral spreading, there is a 7% probability of "at least extensive" damage.

For vertical settlement, a lognormal curve with a median of 10 inches and a dispersion of 1.2 is assumed for the damage state of "at least extensive". 20% of this damage is assumed to be complete. For a PGD of 10" due to vertical settlement, there is a 50% chance of "at least extensive" damage.

- For fault movement or landslide, a lognormal curve with a median of 10 inches and a dispersion of 0.5 is assumed for "complete" damage state. That is, for 10 inches of PGD due to fault movement or landslide, there is a 50% chance of "complete" damage.

An example of how to combine a PGD algorithm with a PGA algorithm for lifeline components was presented in section 7.2.8 of Chapter 7.

**Damage Functions for Water Treatment Plants (due to Ground Shaking)**

PGA related damage functions for water treatment plants are developed with respect to their classification. A total of 24 damage functions are presented. Half of these damage functions correspond to water treatment plants with anchored subcomponents, while the other half correspond to water treatment plants with unanchored subcomponents (see section 7.2.5 for the definition of anchored and unanchored subcomponents). Medians and dispersions of these damage functions are given in Tables 8.3 through 8.5.

Medians and dispersions of damage functions for the water treatment plant subcomponents are summarized in Tables A.8.6 and A.8.7 of Appendix 8A. The medians for elevated pipe damage functions in these tables are based on ATC-13 data (FC-32) for "at grade pipe" using the following MMI to PGA conversion (after G&E, 1994), along with a best-fit lognormal curve.

**Table 8.2: MMI to PGA Conversion (after G&E, 1994)**

| MMI | VI | VII | VIII | IX | X | XI | XII |
|---|---|---|---|---|---|---|---|
| PGA | 0.12 | 0.21 | 0.36 | 0.53 | 0.71 | 0.86 | 1.15 |

Graphical representations of water treatment plant damage functions are also provided. Figures 8.5 through 8.10 are fragility curves for the different classes of water treatment plants.

**Table 8.3: Damage Algorithms for Small Water Treatment Plants**

| Peak Ground Acceleration | | | |
|---|---|---|---|
| **Classification** | **Damage State** | **Median (g)** | **β** |
| Plants with anchored subcomponents ( PWT1) | slight/minor | 0.25 | 0.50 |
| | moderate | 0.38 | 0.50 |
| | extensive | 0.53 | 0.60 |
| | complete | 0.83 | 0.60 |
| Plants with unanchored subcomponents (PWT2) | slight/minor | 0.16 | 0.40 |
| | moderate | 0.27 | 0.40 |
| | extensive | 0.53 | 0.60 |
| | complete | 0.83 | 0.60 |

**Table 8.4: Damage Algorithms for Medium Water Treatment Plants**

| Peak Ground Acceleration | | | |
|---|---|---|---|
| **Classification** | **Damage State** | **Median (g)** | **β** |
| Plants with anchored subcomponents (PWT3) | slight/minor | 0.37 | 0.40 |
| | moderate | 0.52 | 0.40 |
| | extensive | 0.73 | 0.50 |
| | complete | 1.28 | 0.50 |
| Plants with unanchored subcomponents (PWT4) | slight/minor | 0.20 | 0.40 |
| | moderate | 0.35 | 0.40 |
| | extensive | 0.75 | 0.50 |
| | complete | 1.28 | 0.50 |

**Table 8.5: Damage Algorithms for Large Water Treatment Plants**

| Peak Ground Acceleration | | | |
|---|---|---|---|
| **Classification** | **Damage State** | **Median (g)** | **β** |
| Plants with anchored subcomponents (PWT5) | slight/minor | 0.44 | 0.40 |
| | moderate | 0.58 | 0.40 |
| | extensive | 0.87 | 0.45 |
| | complete | 1.57 | 0.45 |
| Plants with unanchored subcomponents (PWT6) | slight/minor | 0.22 | 0.40 |
| | moderate | 0.35 | 0.40 |
| | extensive | 0.87 | 0.45 |
| | complete | 1.57 | 0.45 |

## Damage Functions for Pumping Plants (due to Ground Shaking)

PGA related damage functions for pumping plants are developed with respect to their classification. A total of 16 damage functions are presented. Half of these damage functions correspond to pumping plants with anchored subcomponents, while the other half correspond to pumping plants with unanchored subcomponents. Medians and dispersions of these damage functions are given in Tables 8.6 and 8.7. Graphical representations of damage functions for the different classes of pumping plants are presented in Figures 8.11 through 8.14. Note that medians and dispersions of damage functions for pumping plants' subcomponents are summarized in Appendix 8A.

**Table 8.6: Damage Algorithms for Small Pumping Plants**

| Peak Ground Acceleration | | | |
|---|---|---|---|
| **Classification** | **Damage State** | **Median (g)** | **β** |
| Plants with anchored subcomponents (PPP1) | slight/minor | 0.15 | 0.70 |
| | moderate | 0.36 | 0.65 |
| | extensive | 0.66 | 0.65 |
| | complete | 1.50 | 0.80 |
| Plants with unanchored subcomponents (PPP2) | slight/minor | 0.13 | 0.60 |
| | moderate | 0.28 | 0.50 |
| | extensive | 0.66 | 0.65 |
| | complete | 1.50 | 0.80 |

**Table 8.7: Damage Algorithms for Medium/Large Pumping Plants**

| Peak Ground Acceleration | | | |
|---|---|---|---|
| **Classification** | **Damage State** | **Median (g)** | **β** |
| Plants with anchored subcomponents (PPP3) | slight/minor | 0.15 | 0.75 |
| | moderate | 0.36 | 0.65 |
| | extensive | 0.77 | 0.65 |
| | complete | 1.50 | 0.80 |
| Plants with unanchored subcomponents (PPP4) | slight/minor | 0.13 | 0.60 |
| | moderate | 0.28 | 0.50 |
| | extensive | 0.77 | 0.65 |
| | complete | 1.50 | 0.80 |

**Damage Functions for Wells (due to Ground Shaking)**

A total of four PGA-related damage functions are presented. In developing these damage functions, it is assumed that equipment in wells is anchored. Medians and dispersions of these damage functions are given in Table 8.8. Graphical representations of well damage functions are also shown in Figure 8.15. Note that medians and dispersions of damage functions for well subcomponents are summarized in Appendix 8A.

**Table 8.8: Damage Algorithms for Wells**

| Peak Ground Acceleration | | | |
|---|---|---|---|
| **Classification** | **Damage State** | **Median (g)** | **β** |
| Wells (PWE1) | slight/minor | 0.15 | 0.75 |
| | moderate | 0.36 | 0.65 |
| | extensive | 0.72 | 0.65 |
| | complete | 1.50 | 0.80 |

## Damage Functions for Water Storage tanks

A total of 24 PGA related damage functions are developed. These correspond to on-ground concrete (anchored and unanchored), on ground steel (anchored and unanchored), elevated steel, and on-ground wood tanks. For tanks, anchored and unanchored refers to positive connection, or a lack thereof, between the tank wall and the supporting concrete ring wall. The PGD algorithm associated with these water storage tanks is described at the beginning of section 8.1.8. For buried storage tanks a separate PGD algorithm is presented. Medians and dispersions of the PGA related damage functions are given in Table 8.9. Graphical representations of water storage tank damage functions are also provided. Figures 8.16 through 8.21 are fragility curves for the different classes of water storage tanks.

**Table 8.9: Damage Algorithms for Water Storage Tanks**

| **Peak Ground Acceleration** | | | |
|---|---|---|---|
| **Classification** | **Damage State** | **Median (g)** | **β** |
| On-Ground Anchored Concrete Tank (PST1) | slight/minor<br>moderate<br>extensive<br>complete | 0.25<br>0.52<br>0.95<br>1.64 | 0.55<br>0.70<br>0.60<br>0.70 |
| On-Ground Unanchored Concrete Tank (PST2) | slight/minor<br>moderate<br>extensive<br>complete | 0.18<br>0.42<br>0.70<br>1.04 | 0.60<br>0.70<br>0.55<br>0.60 |
| On-Ground Anchored Steel Tank (PST3) | slight/minor<br>moderate<br>extensive<br>complete | 0.30<br>0.70<br>1.25<br>1.60 | 0.60<br>0.60<br>0.65<br>0.60 |
| On-Ground Unanchored Steel Tank (PST4) | slight/minor<br>moderate<br>extensive<br>complete | 0.15<br>0.35<br>0.68<br>0.95 | 0.70<br>0.75<br>0.75<br>0.70 |
| Above-Ground Steel Tank (PST5) | slight/minor<br>moderate<br>extensive<br>complete | 0.18<br>0.55<br>1.15<br>1.50 | 0.50<br>0.50<br>0.60<br>0.60 |
| On-Ground Wood Tank (PST6) | slight/minor<br>moderate<br>extensive<br>complete | 0.15<br>0.40<br>0.70<br>0.90 | 0.60<br>0.60<br>0.70<br>0.70 |
| **Permanent Ground Deformation** | | | |
| **Classification** | **Damage State** | **Median (in)** | **β** |
| Buried Concrete Tank (PST7) | slight/minor<br>moderate<br>extensive<br>complete | 2<br>4<br>8<br>12 | 0.50<br>0.50<br>0.50<br>0.50 |

## Damage Functions for Buried Pipelines

Two damage algorithms are used for buried pipelines. The first algorithm is associated with peak ground velocity (PGV) while the second algorithm is associated with permanent ground deformation (PGD). Note that in both of these algorithms the diameter of pipe is not considered to be a factor.

The PGV algorithm is based on the empirical data presented in a work done by O'Rourke and Ayala (1993). The data correspond to actual pipeline damage observed in four US and two Mexican earthquakes. This data is plotted in Figure 8.22.a. The following relation represents a good fit for this empircal data:

$$\text{Repair Rate [Repairs/Km]} \cong 0.0001 \text{ x } (\text{PGV})^{(2.25)}$$

With PGV expressed in cm/sec. Note that the data plotted in Figure 8.22.a correspond to asbestos cement, concrete and cast iron pipes; therefore, the above (RR to PGV) relation is assumed to apply for brittle pipelines. For ductile pipelines (steel, ductile iron and PVC), the above relation is multiplied by 0.3. That is, ductile pipelines have 30% of the vulnerability of brittle pipelines. Note that welded steel pipes with arc-welded joints are classified as ductile, and that welded steel pipes with gas-welded joints are classified as brittle. It is conceivable that the only other information available to the user regarding steel pipes is the year of installation. In this case, the user should classify pre-1935 steel pipes as brittle pipes.

The damage algorithm for buried pipelines due to ground failure is based on work conducted by Honegger and Eguchi (1992) for the San Diego County Water Authority (SDCWA). Figure 8.22.b shows the base fragility curve for cast iron pipes. The best-fit function to this curve is given by:

$$\text{Repair Rate [Repairs/Km]} \cong \text{Prob [liq] x PGD}^{(0.56)}$$

With PGD expressed in inches. This RR to PGD relation is assumed to apply for brittle pipelines. For ductile pipelines, the same multiplier as the PGV algorithm is assumed (i.e., 0.3).

To summarize, the pipeline damage algorithms that are used in the current loss estimation methodology are presented in Table 8.10

**Table 8.10: Damage Algorithms for Water Pipelines**

| | PGV Algorithm | | PGD Algorithm | |
|---|---|---|---|---|
| | R. R. ≅ 0.0001 x PGV$^{(2.25)}$ | | R. R. ≅ Prob[liq]xPGD$^{(0.56)}$ | |
| **Pipe Type** | Multiplier | Example of Pipe | Multiplier | Example of Pipe |
| Brittle Pipes (PWP1) | 1 | CI, AC, RCC | 1 | CI, AC, RCC |
| Ductile Pipes (PWP2) | 0.3 | DI, S, PVC | 0.3 | DI, S, PVC |

### 8.1.9 System Performance

In the previous section, damage algorithms for the various components of a water system were presented. For the level 2 enhanced analysis (i.e., assuming the commercial data was readily available and processed as described in the "Potable Water System Analysis Model" manual), this information is combined and a system network analysis is performed.

This section, however, outlines the simplified methodology that is used in the level 1 and level 2 analyses and which allows for a quick evaluation of the system performance in the aftermath of an earthquake.

This approach is based on system performance studies done for water networks in Oakland, Tokyo, and San Francisco. In the Tokyo study (Isoyama and Katayama, 1982), water system network performance evaluations following an earthquake were simulated for two different supply strategies: (1) supply priority to nodes with larger demands, and (2) supply priority to nodes with lowest demands. The "best" and "worst" node performances are approximately reproduced in a different format in Figure 8.23. The probability of pipeline failure, which was assumed to follow a Poisson process in the original paper, was substituded with the average break rate which was backcalculated based on a pipeline link length of about 5 kilometers (i.e., in the trunk network of the water supply system of Tokyo, the average link length is about 5 kilometers). Note that in this figure, serviceability index is considered as a measure of the reduced flow.

Recently, researchers at Cornell University (Markov, Grigoriu and O'Rourke, 1994) evaluated the San Francisco auxiliary (fire fighting) water supply system (AWSS). Some of their results are reproduced and shown also in Figure 8.23.

G&E (1994) also did a similar study for the EBMUD (East Bay Municipal District) water supply system. Their results are shown as well in Figure 8.23.

Based on these results, the damage algorithm proposed in this earthquake loss estimation for the simplified system performance evaluation is defined by a "conjugate" lognormal function (i.e., 1 - lognormal function). This damage function has a median of 0.1

repairs/km and a beta of 0.85, and it is shown in Figure 8.23. Hence, given knowledge of the pipe classification and length, one can estimate the system performance. That is, damage algorithms provided in the previous section give repair rates and therefore the expected total number of repairs (i.e., by multiplying the expected repair rate for each pipe type in the network by its length and summing up over all pipes in the network). The average repair rate is then computed as the ratio of the expected total number of repairs to the total length of pipes in the network.

**Example**

Assume we have a pipeline network of total length equal to 500 kilometers, and that this network is mainly composed of 16" diameter brittle pipes with each segment being 20 feet in length. Assume also that this pipeline is subject to both ground shaking and ground failure as detailed in Table 8.11. Note that the repair rates (R.R.) in this table are computed based on the equations provided in section 8.1.8.

**Table 8.11: Example of System Performance Evaluation**

| PGV (cm/sec) | R.R. (Re/km) | Length (km) | # Repairs | PGD (inches) | Probab. of Lique | R.R. (Re/km) | Length (km) | # Repairs |
|---|---|---|---|---|---|---|---|---|
| 35 | 0.2980 | 50 | ~ 15 | 18 | 1.0 | 5.0461 | 1 | ~ 5 |
| 30 | 0.2106 | 50 | ~ 11 | 12 | 1.0 | 4.0211 | 1 | ~ 4 |
| 25 | 0.1398 | 50 | ~ 7 | 6 | 0.80 | 2.7275 | 5 | ~ 11 |
| 20 | 0.0846 | 50 | ~ 4 | 2 | 0.65 | 1.4743 | 53 | ~ 51 |
| 15 | 0.0443 | 100 | ~ 4 | 1 | 0.60 | 1 | 20 | 12 |
| 10 | 0.0178 | 100 | ~ 2 | 0.5 | 0.40 | 0.6783 | 20 | ~ 6 |
| 5 | 0.0038 | 100 | 0 | 0 | 0.10 | 0 | 400 | 0 |
| | Total | 500 | 43 | | | Total | 500 | 89 |

Therefore, due to PGV, the estimated number of leaks is 80% x 43 = 34, and the estimated number of breaks is 9, while due to PGD, the estimated number of leaks is 20% x 89 = 18 and the estimated number of breaks is 71.

When we apply the "conjugate" lognormal damage function, which has a median of 0.1 repairs/km and a beta of 0.85, first we compute conservatively the average break rate as:

- Average break rate = (9 + 71) / 500 = 0.16 repairs/km

Hence, the serviceability index right after the earthquake is:

- Serviceability Index = 1 - Lognormal(0.16, 0.1, 0.85) = 0.29 or 29 %

### 8.1.10 Guidance for Loss Estimation Using Advanced Data and Models Analysis

For this type of analysis, the expert can use the methodology developed with the flexibility to (1) include a more refined inventory of the water system pertaining to the area of study, (2) include component-specific and system-specific fragility data, and (3) utilize a commercial model to estimate overall system functionality. Default damage algorithms can be modified or replaced to incorporate improved information about key components of a water system. Similarly, better restoration curves can be developed, given knowledge of available resources and a more accurate layout of the water network within the local topographic and geological conditions.

### 8.1.11 References

(1) ATC-13, "Earthquake Damage Evaluation Data for California", Applied Technology Council, Redwood City, CA, 1985.

(2) G&E Engineering Systems, Inc. (G&E), "NIBS Earthquake Loss Estimation Methods, Technical Manual, (Water Systems)", May 1994.

(3) Eguchi R.T., Taylor C., and Hasselman T.K., "Seismic Component Vulnerability Models for Lifeline Risk Analysis", February 1983.

(4) Velon J.P. and Johnson T.J., "Water Distribution and Treatment (Davis Handbook of Applied Hydraulics)", 1993.

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(6) McGhee T.J., " Water Supply and Sewerage, 6th Edition", 1993.

(7) K/J/C and Dames & Moore, "Earthquake Loss Estimation for the City of Everett, Washington Lifelines", May 1991.

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(12) Isoyama R. and Katayama T., "Reliability Evaluation of Water Supply Systems During Earthquakes", February 1982.

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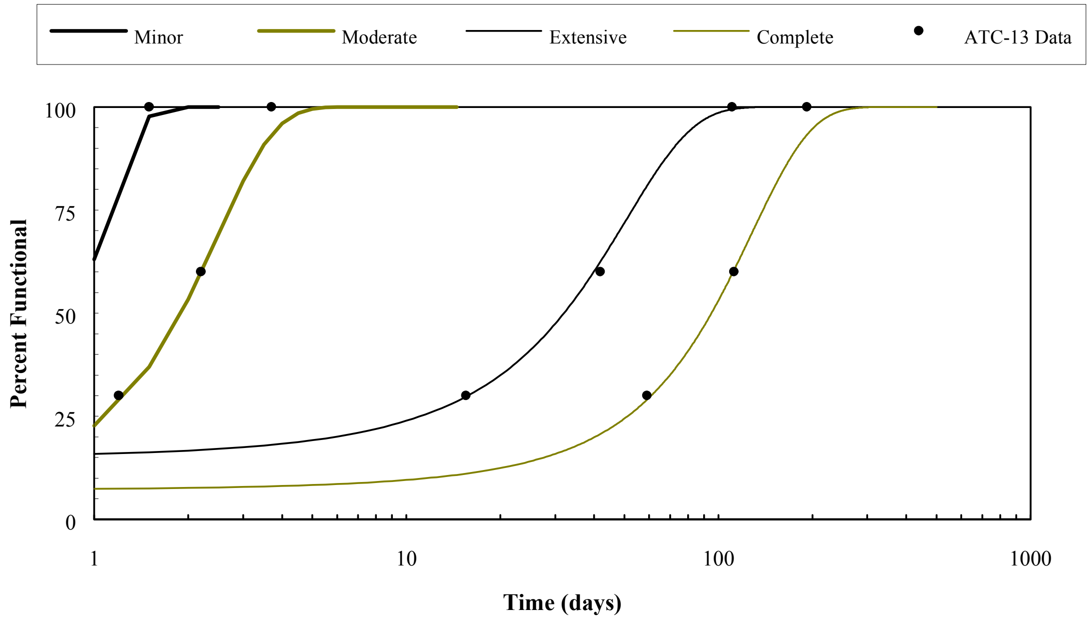


**Figure 8.1: Restoration Curves for Water Treatment Plants (after ATC-13, 1985).**

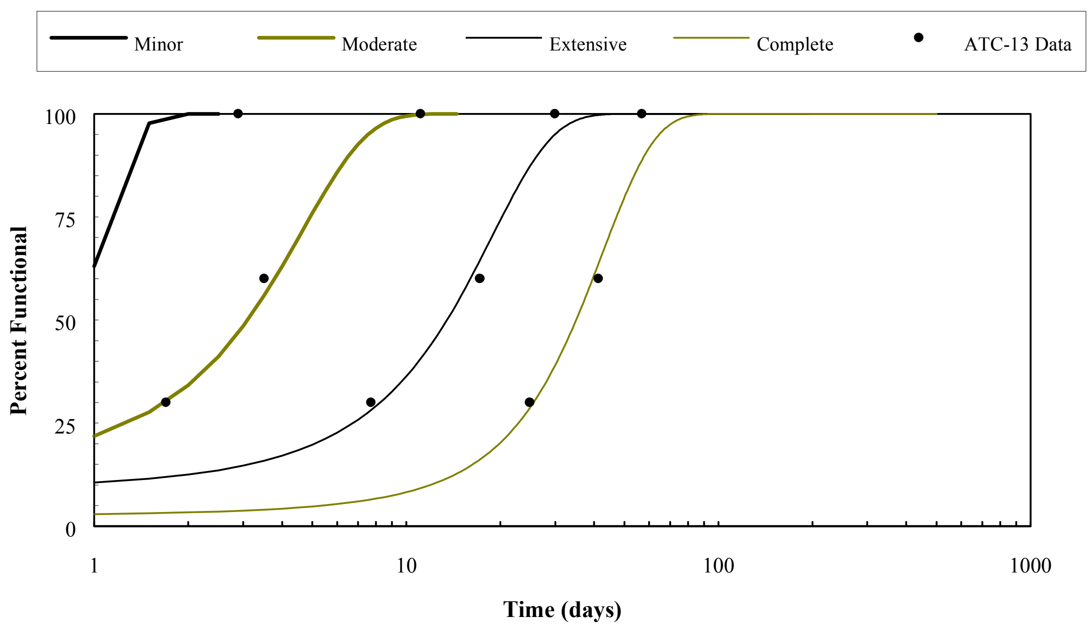


**Figure 8.2: Restoration Curves for Pumping Plants (after ATC-13, 1985).**

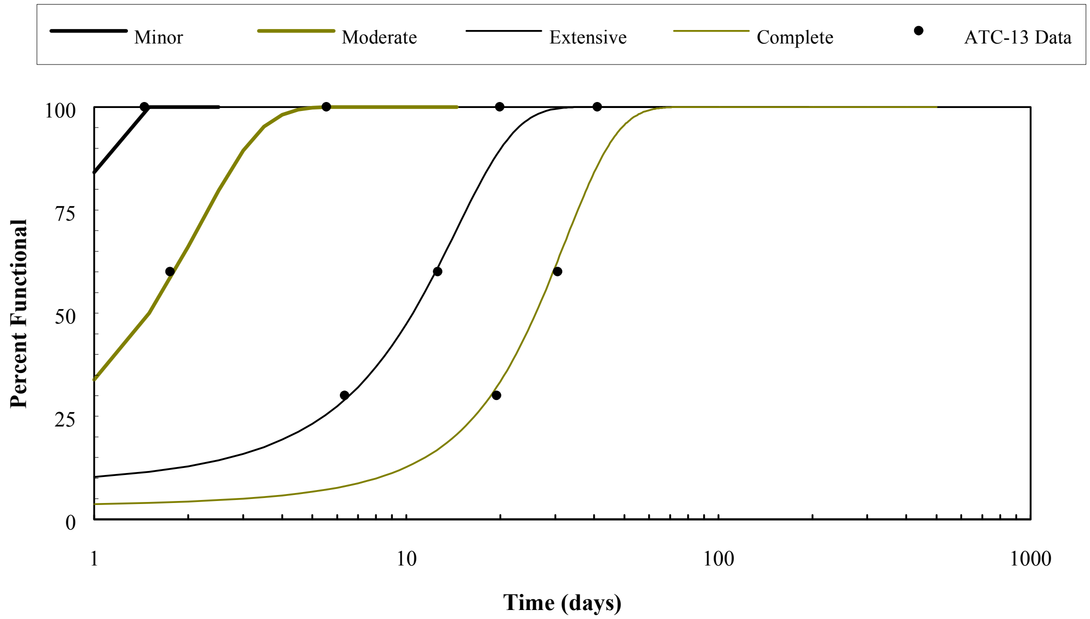


**Figure 8.3: Restoration Curves for Wells (after ATC-13, 1985).**

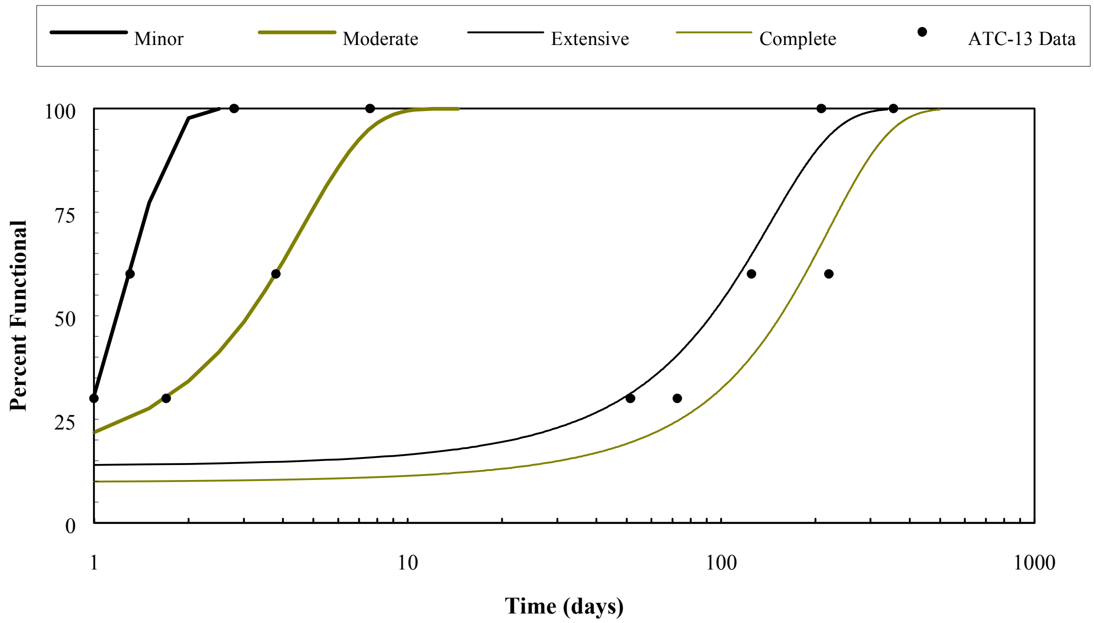


**Figure 8.4: Restoration Curves for Water Storage Tanks (after ATC-13, 1985).**

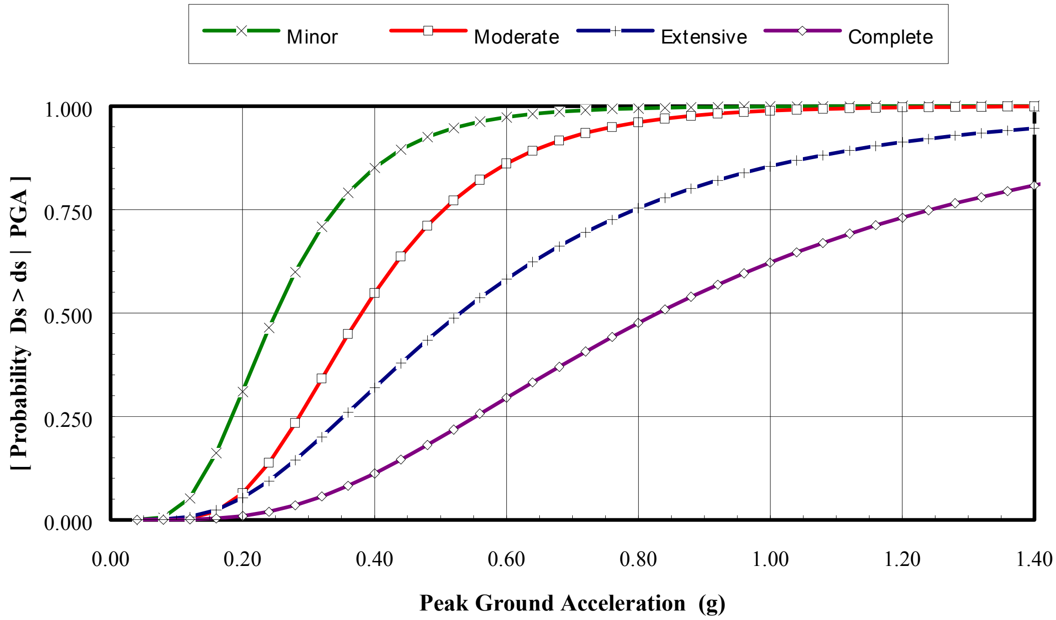


**Figure 8.5: Fragility Curves for Small Water Treatment Plants with Anchored Components.**

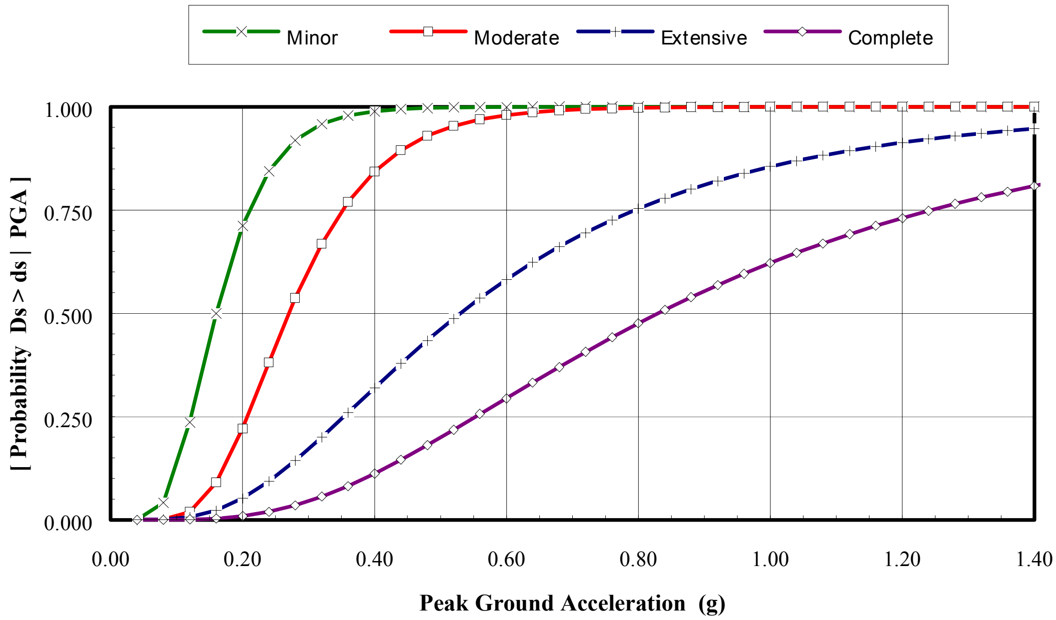


**Figure 8.6: Fragility Curves for Small Water Treatment Plants with Unanchored Components.**

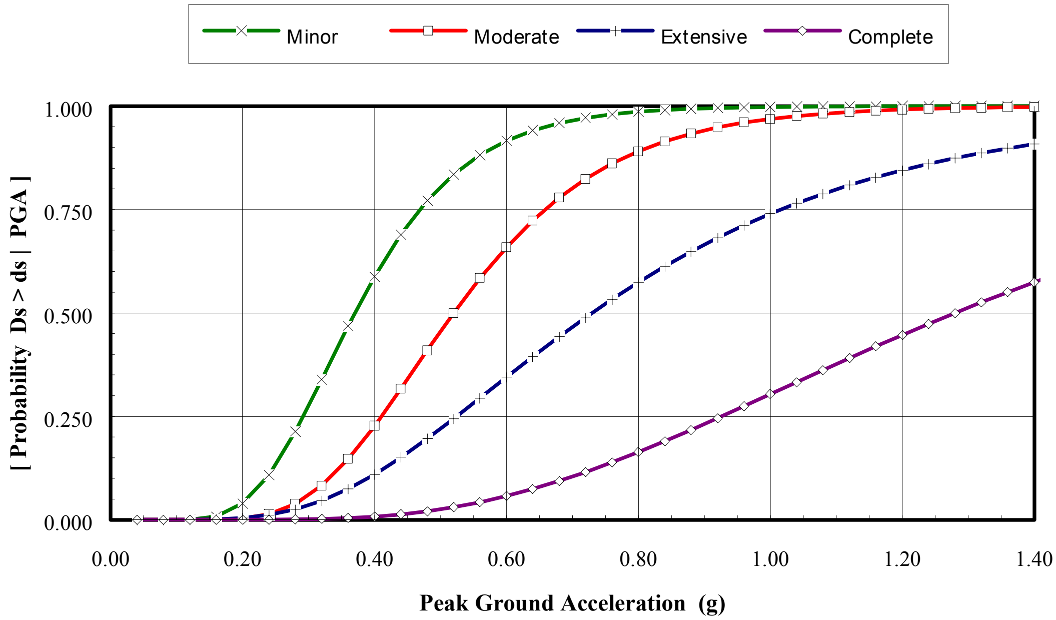


**Figure 8.7:  Fragility Curves for Medium Water Treatment Plants with Anchored Components.**

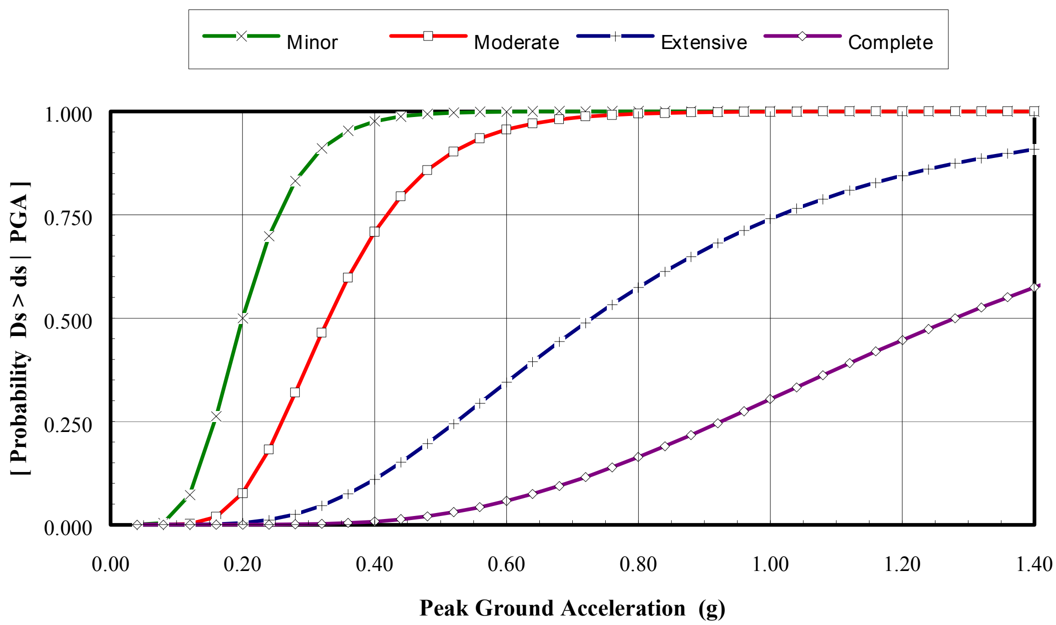


**Figure 8.8:  Fragility Curves for Medium Water Treatment Plants with Unanchored Components.**

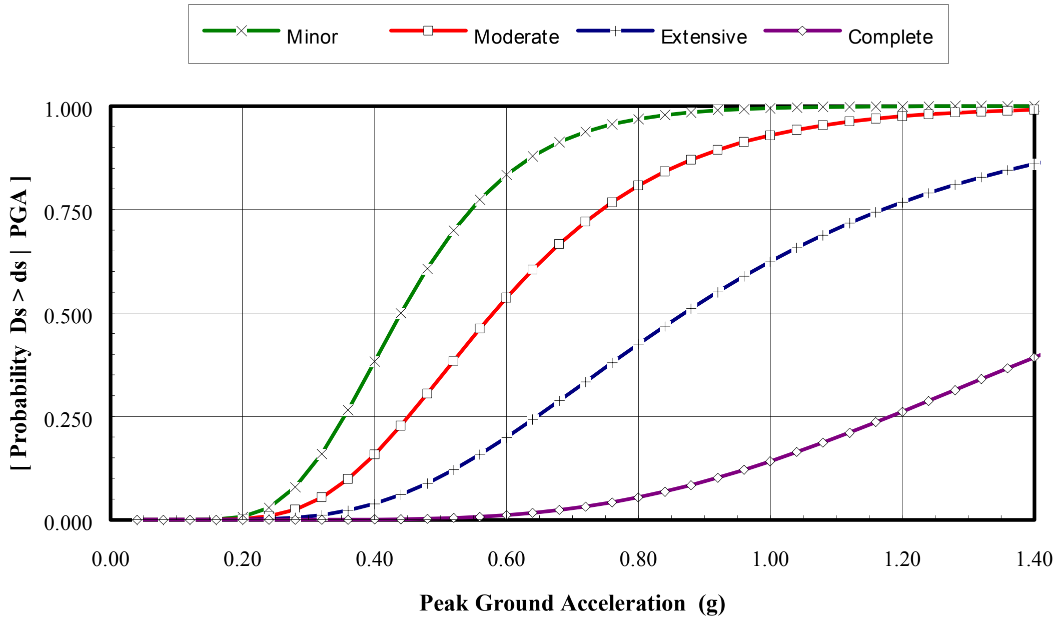


**Figure 8.9: Fragility Curves for Large Water Treatment Plants with Anchored Components.**

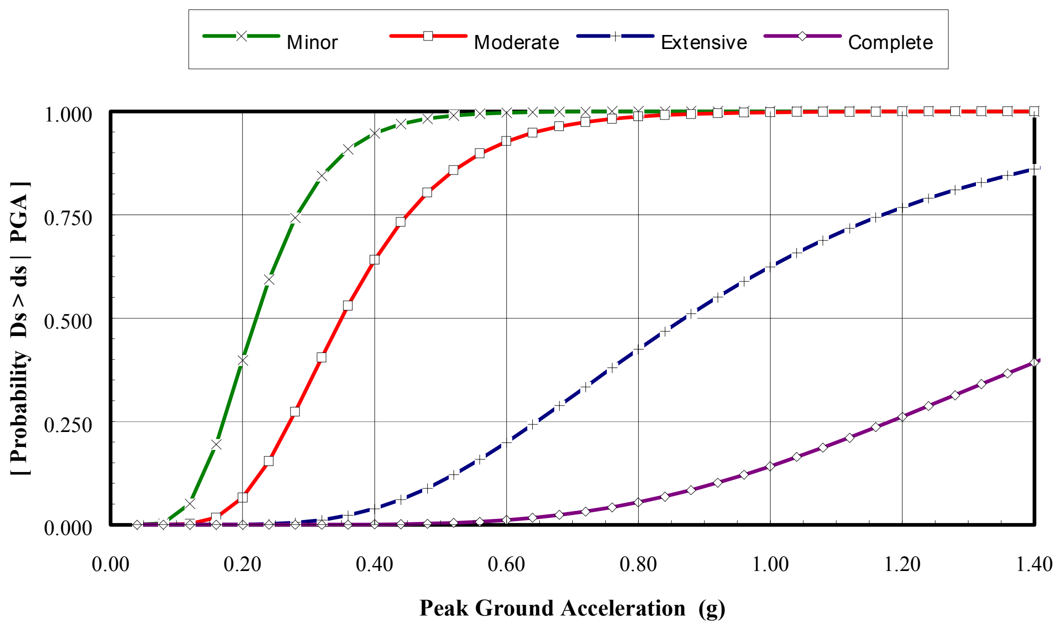


**Figure 8.10: Fragility Curves for Large Water Treatment Plants with Unanchored Components.**

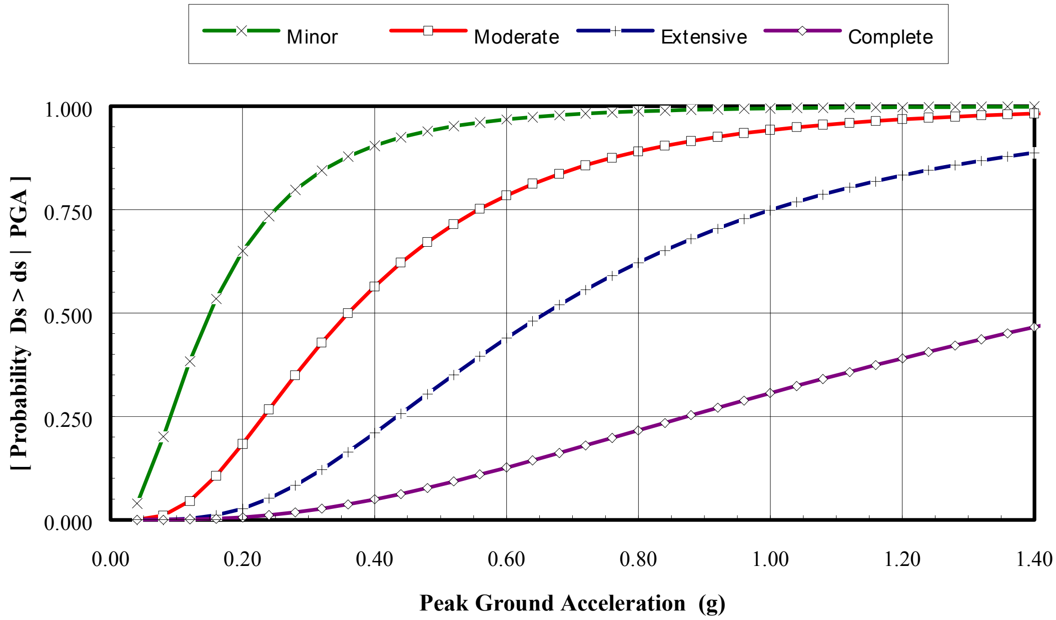


**Figure 8.11: Fragility Curves for Small Pumping Plants with Anchored Components.**

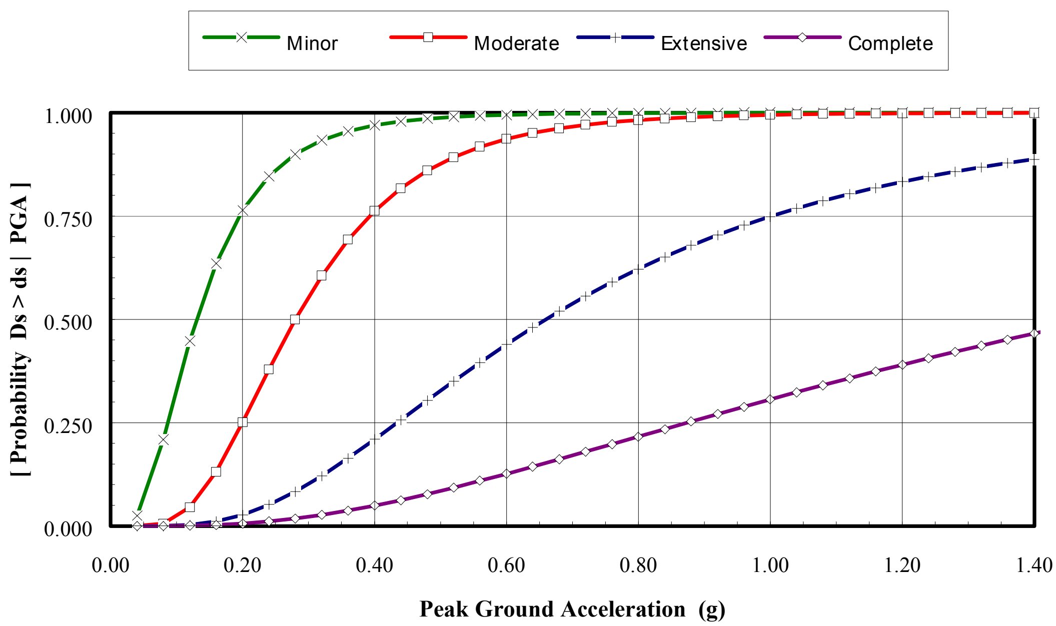


**Figure 8.12: Fragility Curves for Small Pumping Plants with Unanchored Components.**

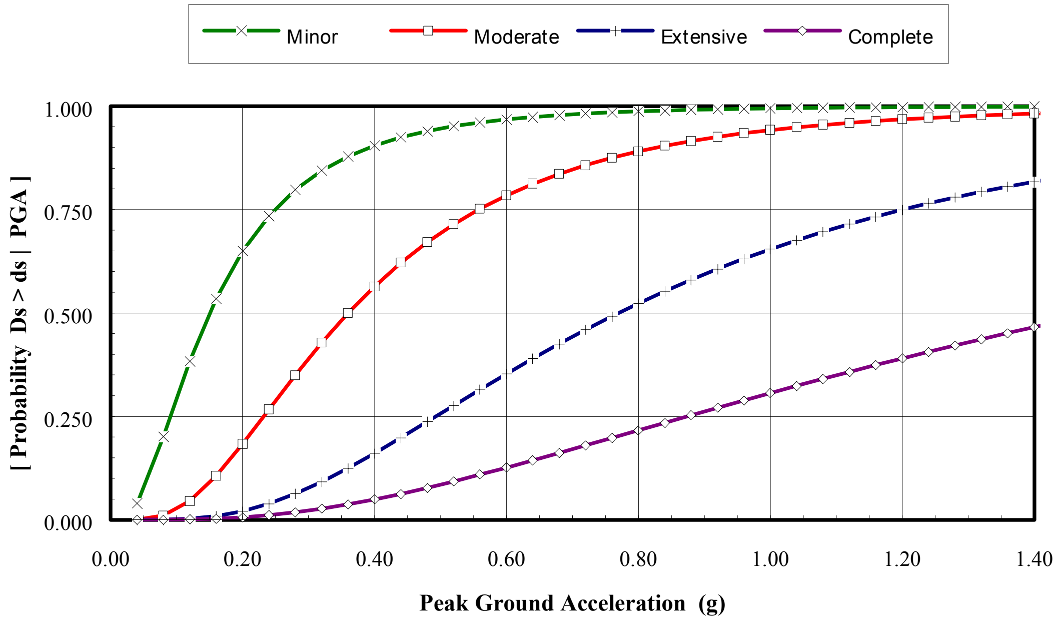


**Figure 8.13:  Fragility Curves for Medium/Large Pumping Plants with Anchored Components.**

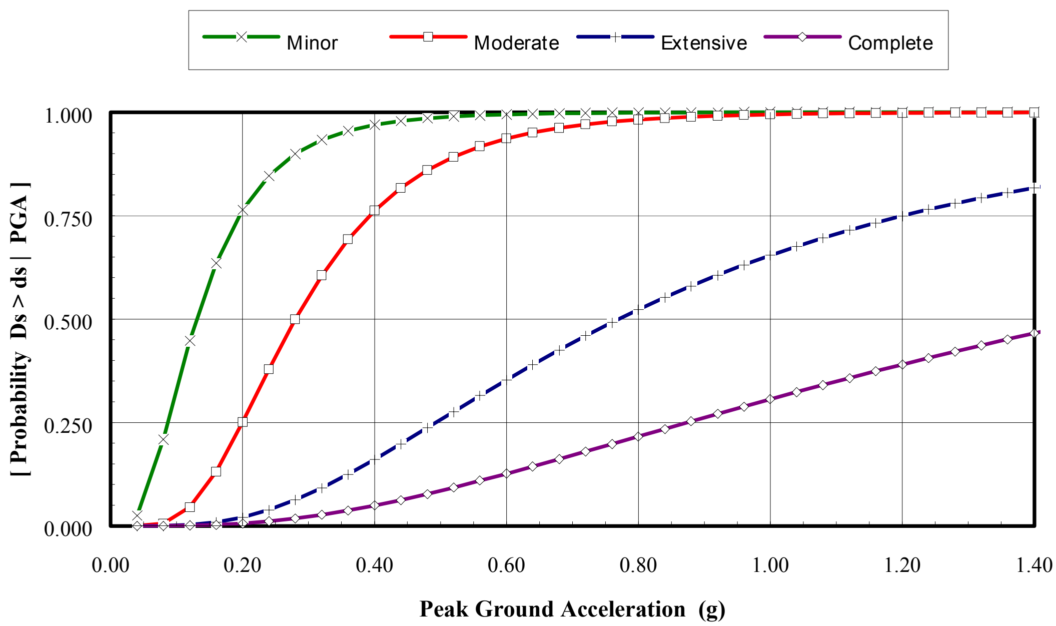


**Figure 8.14:  Fragility Curves for Medium/Large Pumping Plants with Anchored Components.**

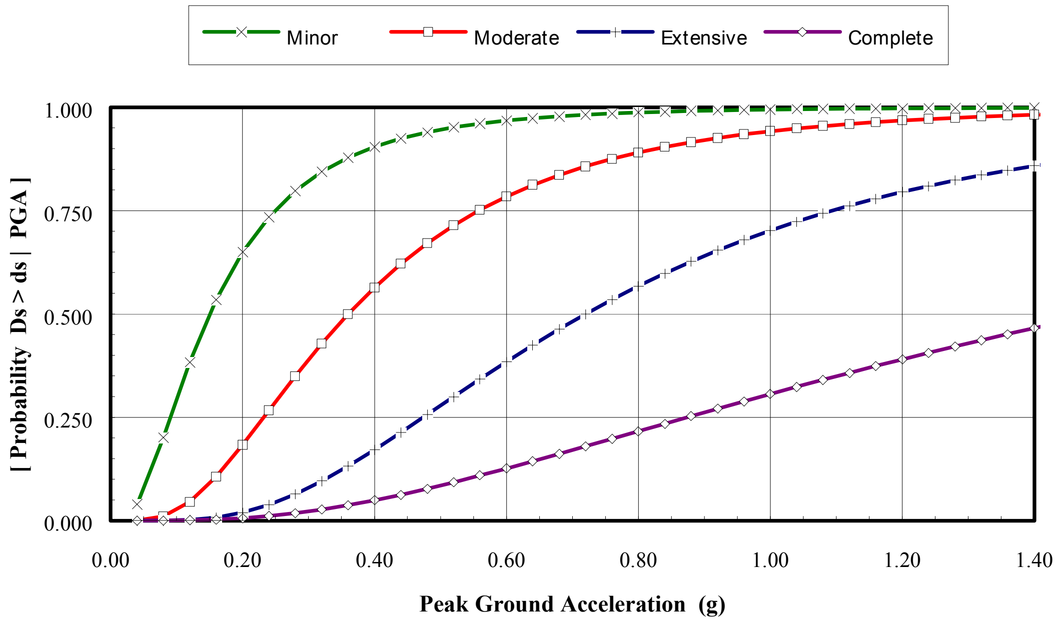


**Figure 8.15:  Fragility Curves for Wells**

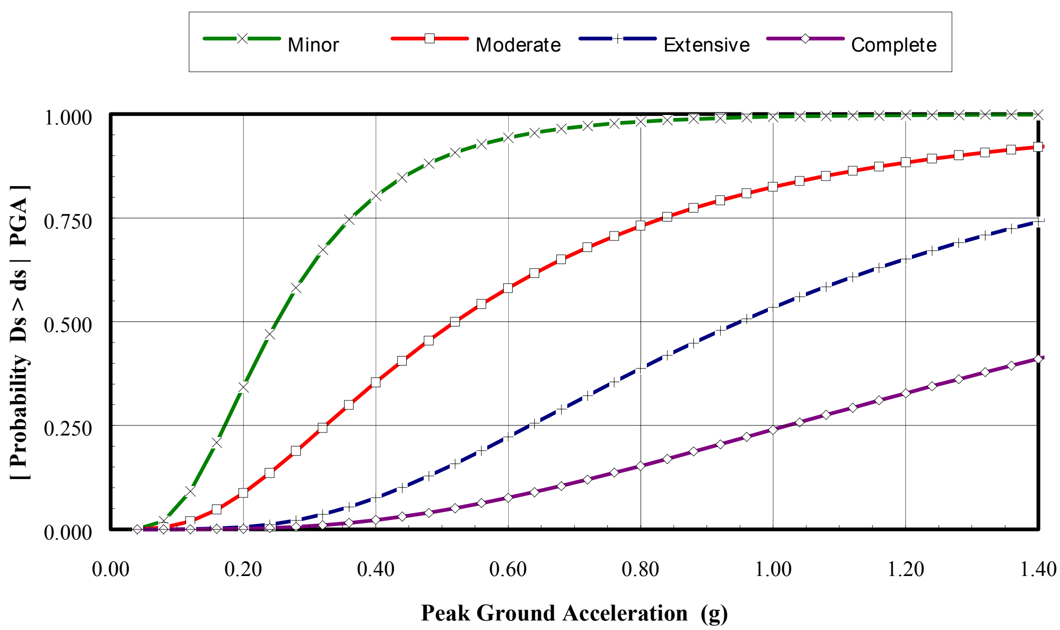


**Figure 8.16:  Fragility Curves for Anchored On Ground Concrete Tank.**

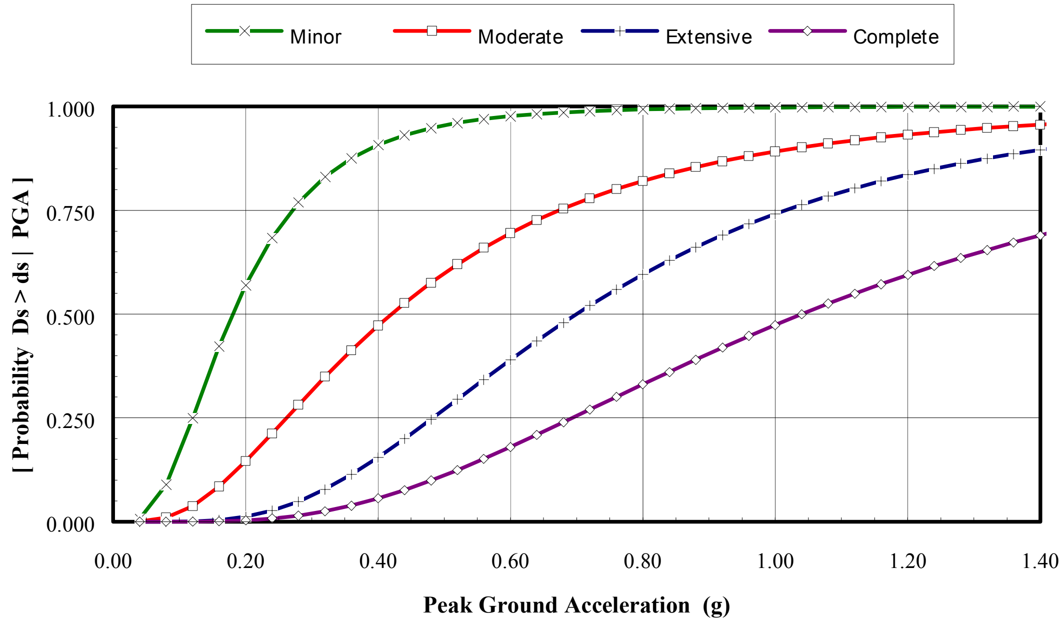


**Figure 8.17: Fragility Curves for Unanchored On Ground Concrete Tank.**

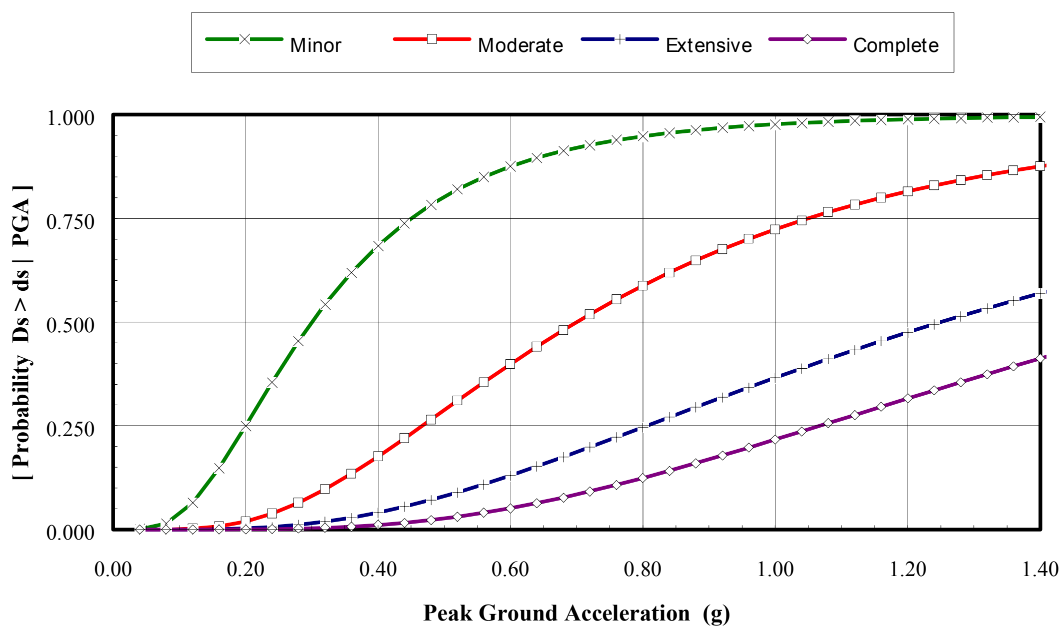


**Figure 8.18: Fragility Curves for Anchored On Ground Steel Tank.**

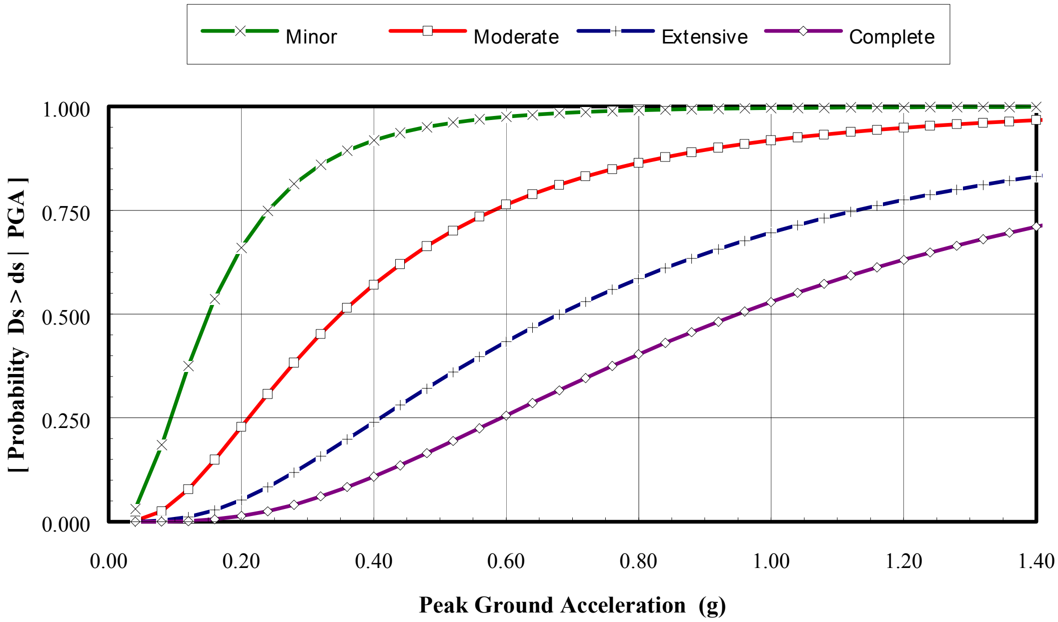


**Figure 8.19: Fragility Curves for Unanchored On Ground Steel Tank.**

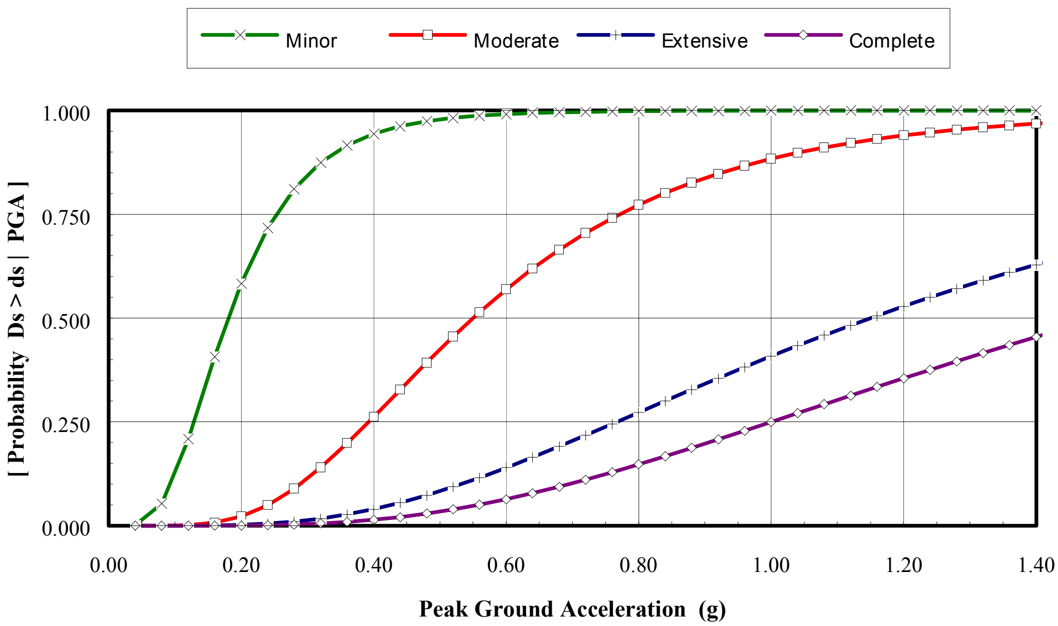


**Figure 8.20: Fragility Curves for Above Ground Steel Tank.**

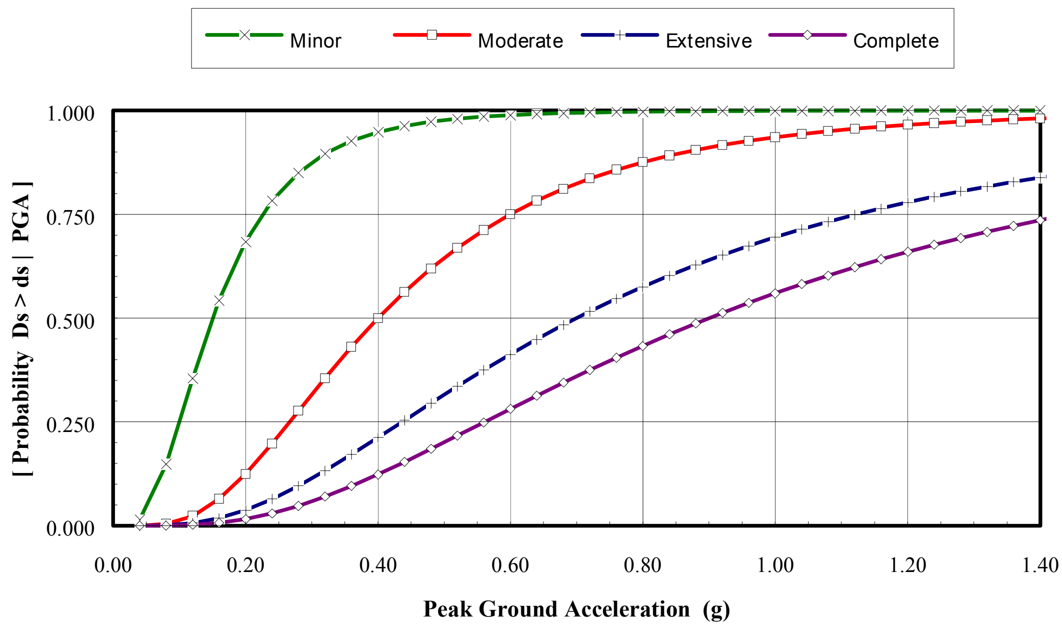


**Figure 8.21: Fragility Curves for On Ground Wood Tank.**

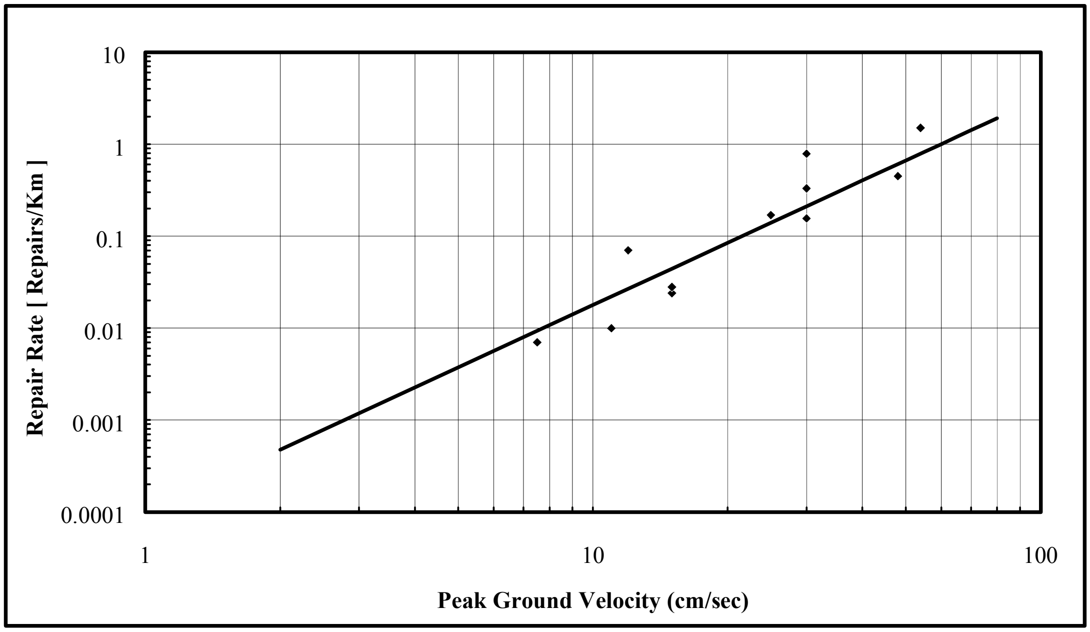


**Figure 8.22.a: Ground Shaking (Wave Propagation) Damage Model for Brittle Pipes (Specifically CI, AC, RCC, and PCCP) Based on Four U.S. and Two Mexican Earthquakes (after O'Rourke and Ayala, 1993).**

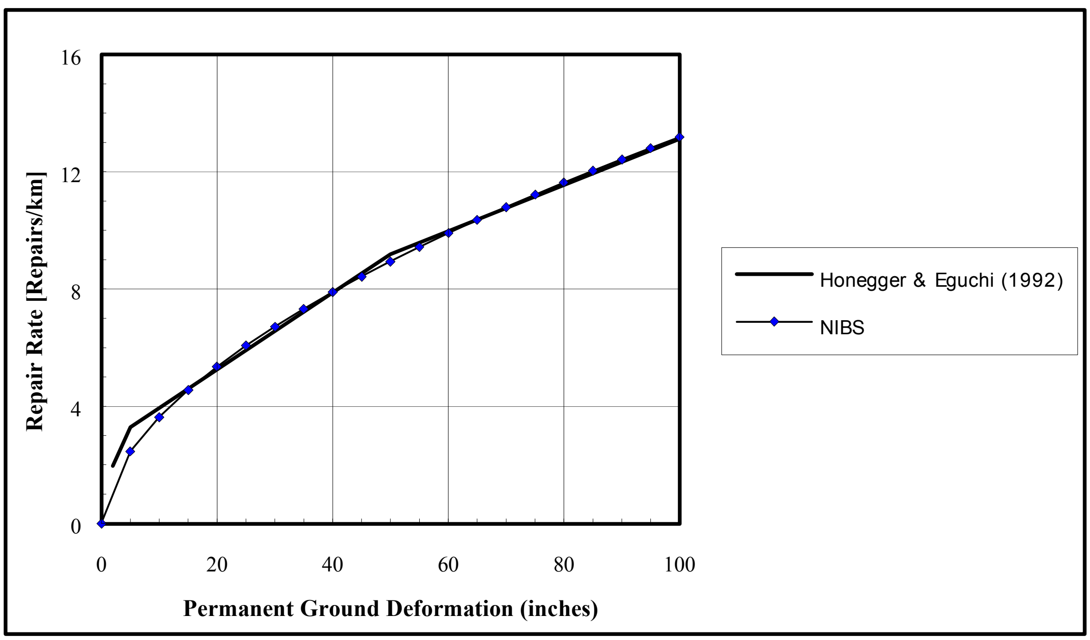


**Figure 8.22.b: Ground Deformation Damage Model for Cast Iron Pipes (after Honegger and Eguchi, 1992).**

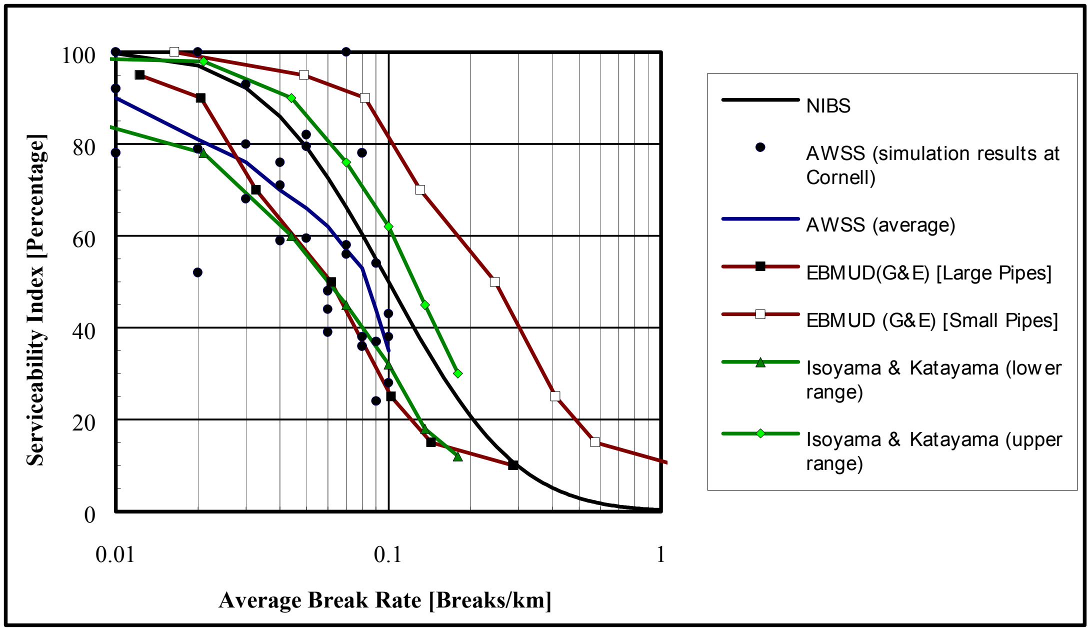


**Figure 8.23: Damage Index Versus Average Break Rate for Post-Earthquake System Performance Evaluation.**

## 8.2 Waste Water Systems

### 8.2.1 Introduction

This section presents a loss estimation methodology for a waste water system during earthquakes. This system consists of transmission, and treatment components. These components are vulnerable to damage during earthquakes, which may result in significant disruption to the utility network.

### 8.2.2 Scope

The scope of this section includes development of methods for estimation of earthquake damage to a waste water system given knowledge of components (i.e., underground sewers and interceptors, waste water treatment plants, and lift stations), classification (i.e., for waste water treatment plants, small, medium or large), and the ground motion (i.e., peak ground velocity, peak ground acceleration and/or permanent ground deformation). Damage states describing the level of damage to each of the waste water system components are defined (i.e., minor, moderate, extensive or complete for facilities plus #repairs/km for sewers/interceptors). Fragility curves are developed for each classification of water system component. These curves describe the probability of reaching or exceeding each damage state given the level of ground motion. Based on these fragility curves, a method for assessing functionality of each component of the waste water system is presented.

### 8.2.3 Input Requirements and Output Information

Required input to estimate damage to waste water systems is listed below.

**<u>Sewers and Interceptors</u>**

- Longitude and latitude of end nodes of links
- Peak ground velocity and permanent ground deformation (PGV and PGD)
- Classification

**<u>Waste Water Treatment Plant and Lift Stations</u>**

- Longitude and latitude of facility
- PGA and PGD
- Classification (small, medium or large, with anchored or unanchored components)

Direct damage output for waste water systems includes probability estimates of (1) component functionality and (2) damage, expressed in terms of the component's damage ratio (repair cost to replacement cost). Note that damage ratios for each of the waste water system components are presented in section 15.3 of Chapter 15.

### 8.2.4 Form of Damage Functions

Damage functions or fragility curves for waste water system components other than sewers and interceptors are modeled as lognormally-distributed functions that give the probability of reaching or exceeding different damage states for a given level of ground motion (quantified in terms of PGA) and ground failure (quantified in terms of PGD). Each of these fragility curves is characterized by a median value of ground motion (or failure) and an associated dispersion factor (lognormal standard deviation). For sewers and interceptors, empirical relations that give the expected repair rates due to ground motion (quantified in terms of PGV) or ground failure (quantified in terms of PGD) are provided.

Definitions of various damage states and the methodology used in deriving all these fragility curves are presented in the next section.

### 8.2.5 Description of Waste Water System Components

As mentioned before, a waste water system typically consists of collection sewers, interceptors, lift stations, and wastewater treatment plants. In this section, a brief description of each of these components is given.

**Collection Sewers**

Collection sewers are generally closed conduits that carry normally sewage with a partial flow. Collection sewers could be sanitary sewers, storm sewers, or combined sewers. Pipe materials that are used for potable water transportation may also be used for wastewater collection. The most commonly used sewer material is clay pipe manufactored with integral bell and spigot end. These pipes range in size from 4 to 42 inches in diameter. Concrete pipes are mostly used for storm drains and for sanitary sewers carrying noncorrosive sewage (i.e. with organic materials). For the smaller diameter range, plastic pipes are also used.

**Interceptors**

Interceptors are large diameter sewer mains. They are usually located at the lowest elevation areas. Pipe materials that are used for interceptor sewers are similar to those used for collection sewers.

**Lift Stations (LS)**

Lift stations are important parts of the waste water system. Lift stations serve to raise sewage over topographical rises. If the lift station is out of service for more than a short time, untreated sewage will either spill out near the lift station, or back up into the collection sewer system.

In this study, lift stations are classified as either small LS (capacity less than 10 mgd) or medium/large LS (capacity greater than 10 mgd). Lift stations are also classified as having either anchored or unanchored subcomponents (see section 7.2.5 for the definition of anchored and unanchored subcomponents)

**Waste Water Treatment Plants (WWTP)**

Three sizes of wastewater treatment plants are considered: small (capacity less than 50 mgd), medium (capacity between 50 and 200 mgd), and large (capacity greater than 200 mgd). WWTP has the same processes existing in WTP with the addition of secondary treatment subcomponents.

### 8.2.6 Definitions of Damage States

Waste water systems are susceptible to earthquake damage. Facilities such as waste water treatment plants and lift stations are mostly vulnerable to PGA, and sometimes PGD, if located in liquefiable or landslide zones. Therefore, the damage states for these components are defined and associated with PGA and PGD. Sewers, on the other hand, are vulnerable to PGV and PGD. Therefore, the damage algorithms for these components are associated with those two ground motion parameters.

#### 8.2.6.1 Damage States Definitions for Components other than Sewers/Interceptors

A total of five damage states are defined for waste water system components other than sewers and interceptors. These are none ($ds_1$), slight/minor ($ds_2$), moderate ($ds_3$), extensive ($ds_4$) and complete ($ds_5$).

**Slight/Minor Damage ($ds_2$)**

- **For waste water treatment plants**, $ds_2$ is defined as for WTP in potable water systems.
- **For lift stations**, $ds_2$ is defined as for pumping plants in potable water systems.

**Moderate Damage ($ds_3$)**

- **For waste water treatment plants**, $ds_3$ is defined as for WTP in potable water systems.
- **For lift stations**, $ds_3$ is defined as for pumping plants in potable water systems.

**Extensive Damage ($ds_4$)**

- **For waste water treatment plants**, $ds_4$ is defined as for WTP in potable water systems.
- **For lift stations**, $ds_4$ is defined as for pumping plants in potable water systems.

**Complete Damage ($ds_5$)**

- **For waste water treatment plants**, $ds_5$ is defined as for WTP in potable water systems.
- **For lift stations**, $ds_5$ is defined as for pumping plants in potable water systems.

#### 8.2.6.2 Damage States Definitions for Sewers/Interceptors

For sewers/interceptors, two damage states are considered. These are leaks and breaks. Generally, when a sewer/interceptor is damaged due to ground failure, the type of damage is likely to be a break, while when a sewer/interceptor is damaged due to seismic wave propagation; the type of damage is likely to be joint pullout or crushing at the bell. In the loss methodology, it is assumed that damage due to seismic waves will consist of 80% leaks and 20% breaks, while damage due to ground failure will consist of 20% leaks and 80% breaks. The user can override these default percentages.

### 8.2.7 Component Restoration Curves

The restoration curves for waste water system components are based on ATC-13 expert data (SF-31.a through SF-331.c). Restoration data for lift stations, and wastewater treatment plants, in the form of dispersions of the restoration functions, are given in Table 8.12.a. The restoration functions are shown in Figures 8.24 and 8.25. Figure 8.24 represents the restoration functions for lift stations and Figure 8.25 represents the restoration curves for wastewater treatment plants. The discretized restoration functions are presented in Table 8.12.b, where the restoration percentage is shown at discretized times. Restoration functions for sewers and interceptors are also presented in Tables 8.12.a and 8.12.b.

**Table 8.12.a: Restoration Functions for Waste Water System Components**

| Restoration Functions (All Normal Distributions) | | | |
|---|---|---|---|
| **Classification** | **Damage State** | **Mean (Days)** | **σ** |
| Lift Stations | slight/minor | 1.3 | 0.7 |
| | moderate | 3.0 | 1.5 |
| | extensive | 21.0 | 12.0 |
| | complete | 65.0 | 25.0 |
| Waste Water Treatment Plants | slight/minor | 1.5 | 1.0 |
| | moderate | 3.6 | 2.5 |
| | extensive | 55.0 | 25.0 |
| | complete | 160.0 | 60.0 |
| Sewers/Interceptors | leak | 3.0 | 2.0 |
| | break | 7.0 | 4.0 |

**Table 8.12.b: Discretized Restoration Functions for Waste Water System Components**

| Discretized Restoration Functions | | | | | | |
|---|---|---|---|---|---|---|
| **Classification** | **Damage State** | **1 day** | **3 days** | **7 days** | **30 days** | **90 days** |
| Lift Stations | slight/minor | 34 | 100 | 100 | 100 | 100 |
| | moderate | 10 | 50 | 100 | 100 | 100 |
| | extensive | 5 | 7 | 13 | 78 | 100 |
| | complete | 0 | 1 | 2 | 9 | 85 |
| Waste Water Treatment Plants | slight/minor | 31 | 94 | 100 | 100 | 100 |
| | moderate | 15 | 40 | 92 | 100 | 100 |
| | extensive | 2 | 2 | 3 | 16 | 92 |
| | complete | 1 | 1 | 1 | 2 | 13 |
| Sewers/Interceptors | leak | 16 | 50 | 98 | 100 | 100 |
| | break | 7 | 16 | 50 | 100 | 100 |

### 8.2.8 Development of Damage Functions

In this subsection, damage functions for the various components of a waste water system are presented. In cases where the components are made of subcomponents (i.e., waste water treatment plants and lift stations), fragility curves for these components are based on the probabilistic combination of subcomponent damage functions using Boolean expressions to describe the relationship of subcomponents. The Boolean logic is implicitly presented within the definition of a particular damage state (see section 8.1.8 for an example).

Damage functions due to ground failure (i.e., PGD) for waste water treatment plants and lift stations are assumed to be similar to those described for potable water system facilities in section 8.1.8.

**Damage Functions for Lift Stations**

Damage functions for lift stations are similar to those of pumping plants in potable water systems described in Section 8.1.8.

**Damage Functions for Waste Water Treatment Plants (due to Ground Shaking)**

Tables 8.13 through 8.15 present damage functions for small, medium and large wastewater treatment plants, respectively.  Graphical representations of wastewater treatment plant damage functions are shown in Figures 8.26 through 8.31.  The medians and dispersions of damage functions to waste water treatment plants subcomponents are summarized in Tables B.8.1 and B.8.2 of Appendix 8B.

**Table 8.13:  Damage Algorithms for Small Waste Water Treatment Plants**

| Peak Ground Acceleration | | | |
|---|---|---|---|
| **Classification** | **Damage State** | **Median (g)** | **β** |
| Plants with anchored components (WWT1) | slight/minor | 0.23 | 0.40 |
| | moderate | 0.35 | 0.40 |
| | extensive | 0.48 | 0.50 |
| | complete | 0.80 | 0.55 |
| Plants with unanchored components (WWT2) | slight/minor | 0.16 | 0.40 |
| | moderate | 0.26 | 0.40 |
| | extensive | 0.48 | 0.50 |
| | complete | 0.80 | 0.55 |

**Table 8.14:  Damage Algorithms for Medium Waste Water Treatment Plants**

| Peak Ground Acceleration | | | |
|---|---|---|---|
| **Classification** | **Damage State** | **Median (g)** | **β** |
| Plants with anchored components (WWT3) | slight/minor | 0.33 | 0.40 |
| | moderate | 0.49 | 0.40 |
| | extensive | 0.70 | 0.45 |
| | complete | 1.23 | 0.55 |
| Plants with unanchored components (WWT4) | slight/minor | 0.20 | 0.40 |
| | moderate | 0.33 | 0.40 |
| | extensive | 0.70 | 0.45 |
| | complete | 1.23 | 0.55 |

**Table 8.15: Damage Algorithms for Large Waste Water Treatment Plants**

| Peak Ground Acceleration | | | |
|---|---|---|---|
| **Classification** | **Damage State** | **Median (g)** | **β** |
| Plants with anchored components (WWT5) | slight/minor | 0.40 | 0.40 |
| | moderate | 0.56 | 0.40 |
| | extensive | 0.84 | 0.40 |
| | complete | 1.50 | 0.40 |
| Plants with unanchored components (WWT6) | slight/minor | 0.22 | 0.40 |
| | moderate | 0.35 | 0.40 |
| | extensive | 0.84 | 0.40 |
| | complete | 1.50 | 0.40 |

**Damage Functions for Sewers and Interceptors**

The same two damage algorithms proposed for buried pipelines in potable water systems are assumed to apply for sewers and interceptors. These are listed again in Table 8.16. Note that R.R. stands for repair rates or number of repairs per kilometer, PGV stands for peak ground velocity in cm/sec, and PGD stands for permanent ground deformation in inches.

**Table 8.16: Damage Algorithms for Sewers/Interceptors**

| | **PGV Algorithm** | | **PGD Algorithm** | |
|---|---|---|---|---|
| | R. R. $\cong$ 0.0001 x $PGV^{(2.25)}$ | | R. R. $\cong$ Prob[liq]x$PGD^{(0.56)}$ | |
| **Pipe Type** | Multiplier | Example of Pipe | Multiplier | Example of Pipe |
| Brittle Sewers/Interceptors (WWP1) | 1 | Clay, Concrete | 1 | Clay, Concrete |
| Ductile Sewers/Interceptors (WWP2) | 0.3 | Plastic | 0.3 | Plastic |

## 8.2.9 Guidance for Loss Estimation with Advanced Data and Models Analysis

For this type of analysis, the expert can use the methodology developed with the flexibility to (1) include a more refined inventory of the waste water system pertaining to the area of study, and (2) include component-specific and system-specific fragility data. Default damage algorithms for User-Supplied Data Analysis, can be modified or replaced to incorporate improved information about key components of a waste water system. Similarly, better restoration curves can be developed, given knowledge of available resources and a more accurate layout of the wastewater network within the local topographic and geological conditions.

### 8.2.10 References

(1) ATC-13, "Earthquake Damage Evaluation Data for California", Applied Technology Council, Redwood City, CA, 1985.

(2) G&E Engineering Systems, Inc. (G&E), "NIBS Earthquake Loss Estimation Methods, Technical Manual, (Waste Water Systems)", June 1994.

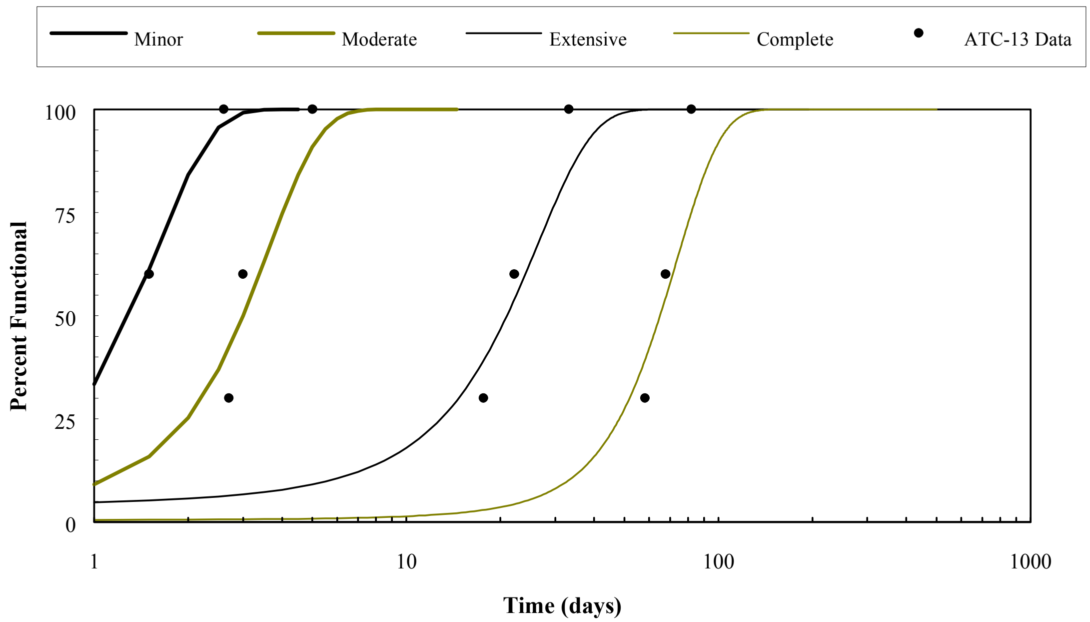


**Figure 8.24: Restoration Curves for Lift Stations.**

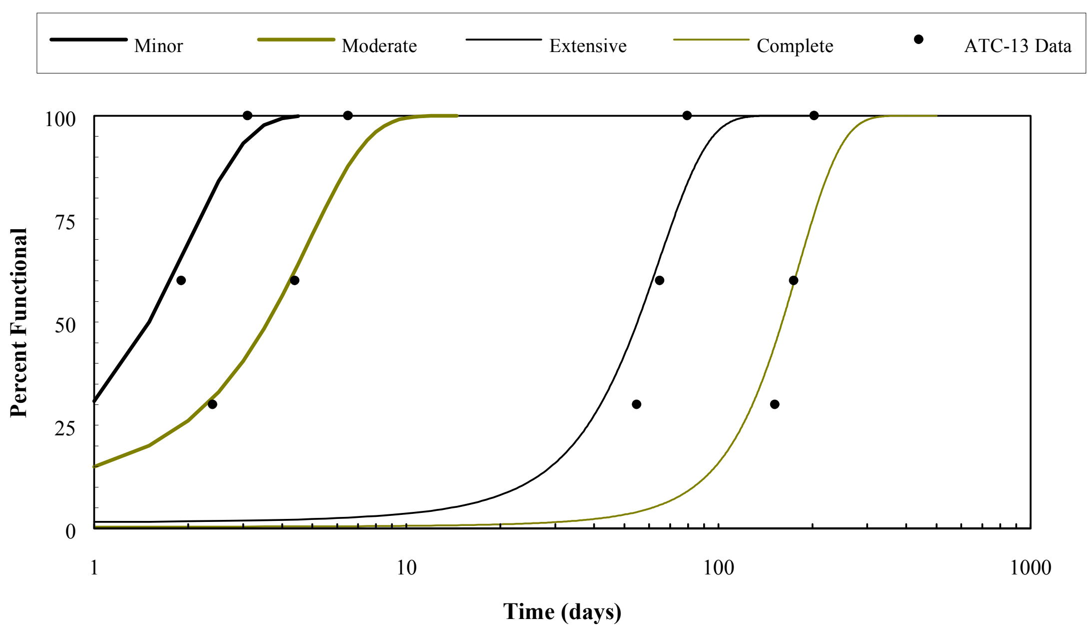


**Figure 8.25: Restoration Curves for Waste Water Treatment Plants.**

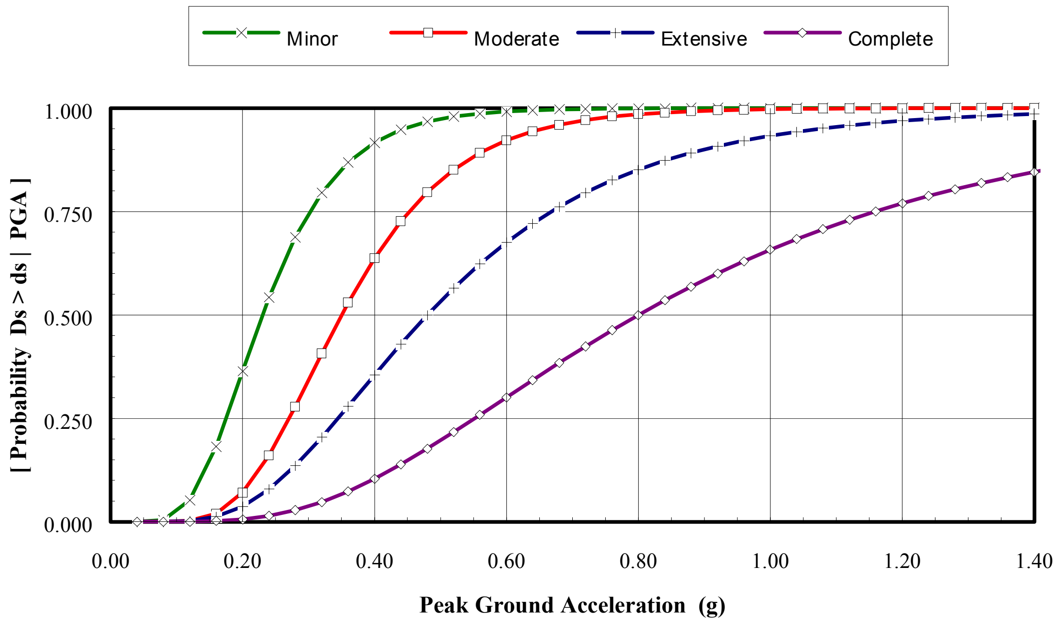


**Figure 8.26:  Fragility Curves for Small Waste Water Treatment Plants with Anchored Components.**

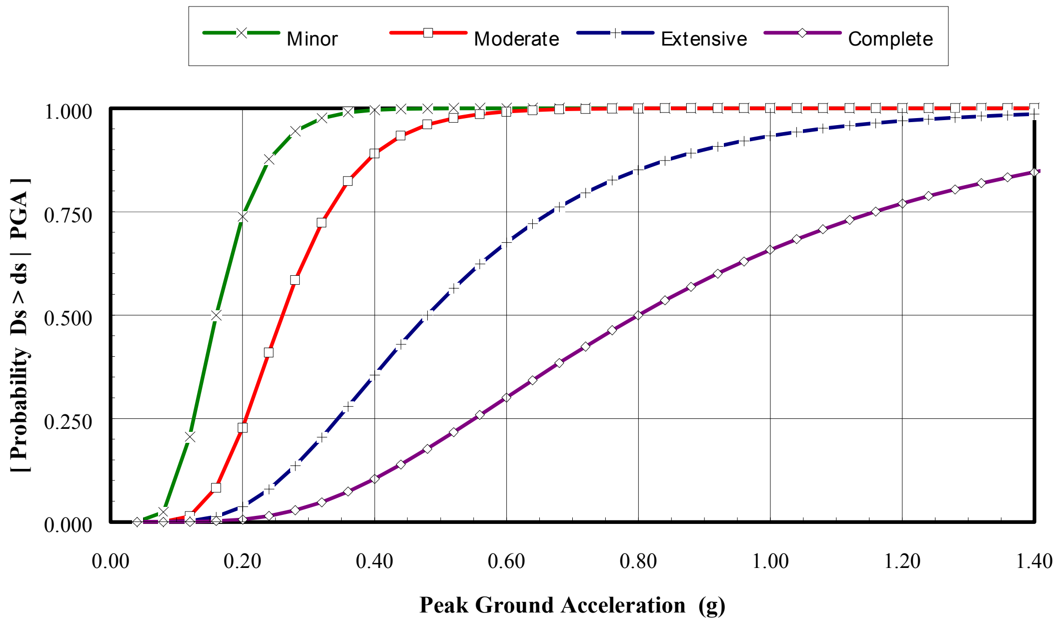


**Figure 8.27:  Fragility Curves for Small Waste Water Treatment Plants with Unanchored Components.**

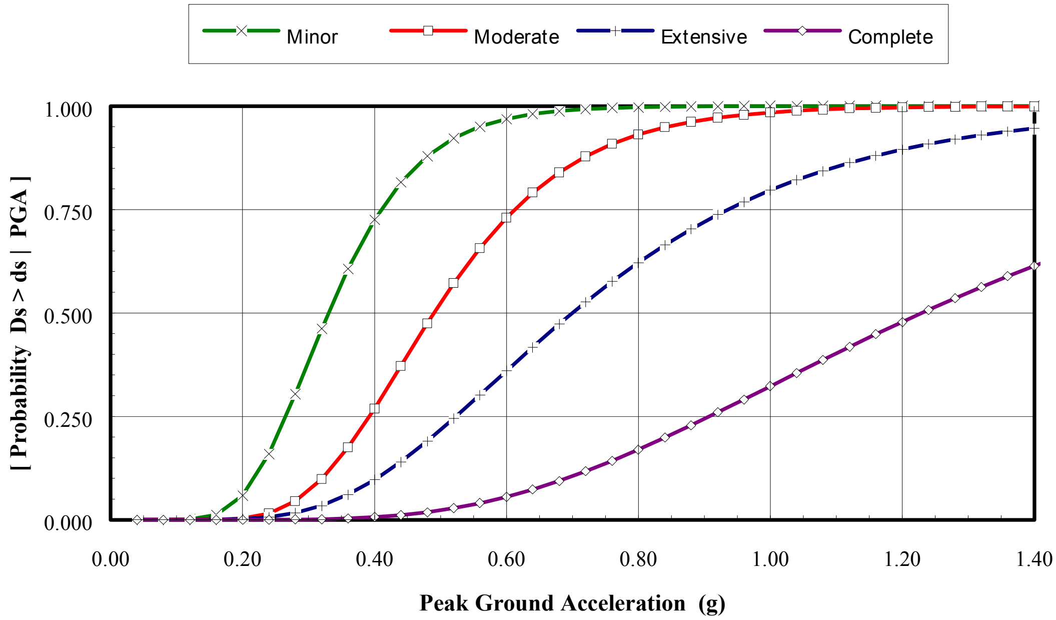


**Figure 8.28: Fragility Curves for Medium Waste Water Treatment Plants with Anchored Components.**

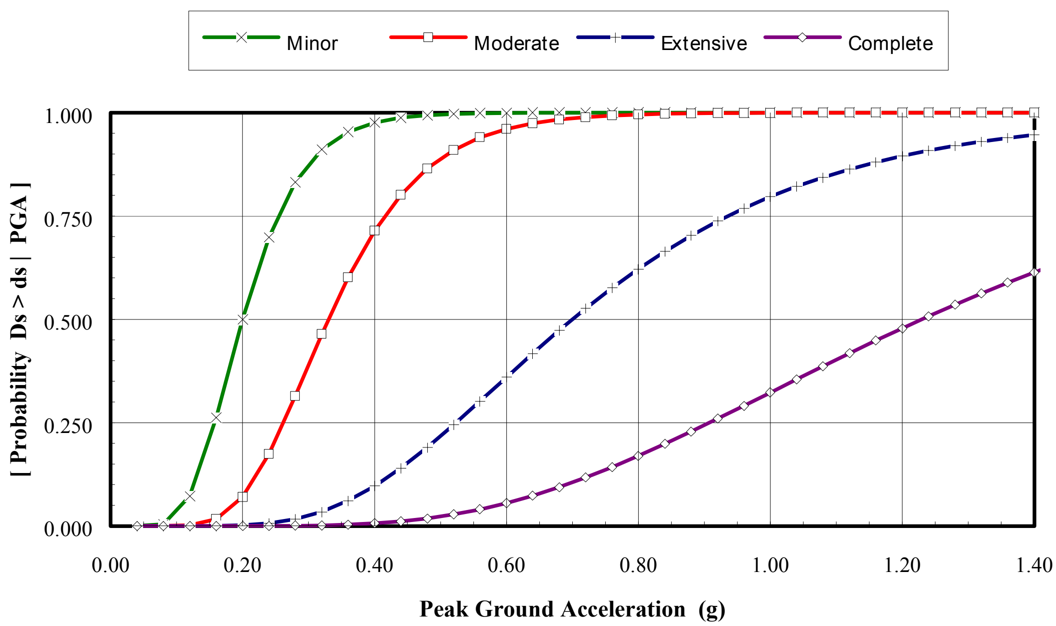


**Figure 8.29: Fragility Curves for Medium Waste Water Treatment Plants with Unanchored Components.**

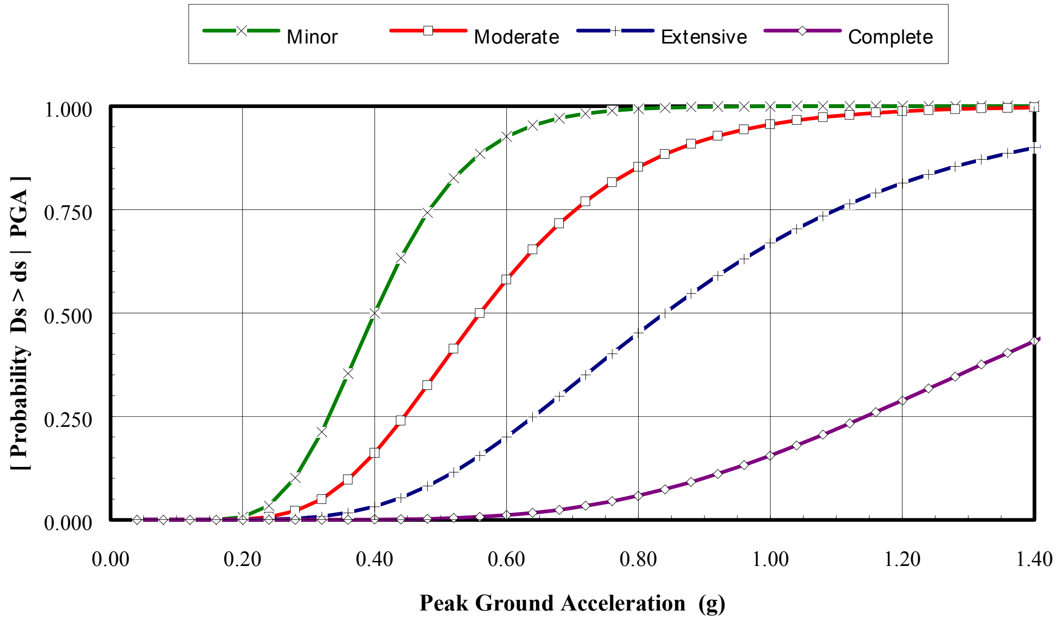


**Figure 8.30: Fragility Curves for Large Waste Water Treatment Plants with Anchored Components.**

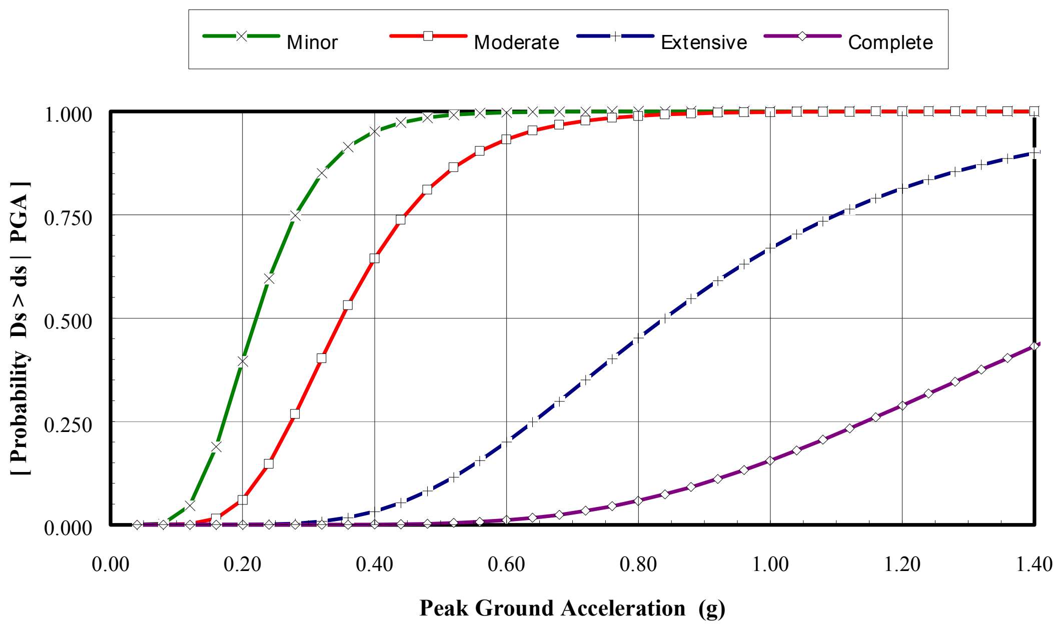


**Figure 8.31: Fragility Curves for Large Waste Water Treatment Plants with Unanchored Components.**

## 8.3 Oil Systems

### 8.3.1 Introduction

This section presents a loss estimation methodology for an oil system during earthquakes. This system consists of refineries and transmission components. These components are vulnerable to damage during earthquakes, which may result in significant disruption to this utility network.

### 8.3.2 Scope

The scope of this section includes development of methods for estimation of earthquake damage to an oil system given knowledge of components (i.e. refineries, pumping plants, and tank farms), classification (i.e. for refineries, with anchored or unanchored components), and the ground motion (i.e. peak ground velocity, peak ground acceleration and/or permanent ground deformation). Damage states describing the level of damage to each of the oil system components are defined (i.e. minor, moderate, extensive or complete, plus # repairs/km for pipelines). Fragility curves are developed for each classification of the oil system component. These curves describe the probability of reaching or exceeding each damage state given the level of ground motion.

Based on these fragility curves, a method for assessing functionality of each component of the oil system is presented.

### 8.3.3 Input Requirements and Output Information

Required input to estimate damage to oil described are listed below.

**Refineries, Pumping Plants and Tank Farms**

- Longitude and latitude of facility
- PGA and PGD
- Classification (small, medium/large, with anchored or unanchored components)

**Oil Pipelines**

- Geographical location of pipe links (longitude and latitude of end nodes)
- Peak ground velocity and permanent ground deformation (PGV and PGD)
- Classification

Direct damage output for oil systems includes probability estimates of (1) component functionality and (2) damage, expressed in terms of the component's damage ratio (repair cost to replacement cost). Note that damage ratios for each of the oil system components are presented in section 15.3 of Chapter 15.

### 8.3.4 Form of Damage Functions

Damage functions or fragility curves for oil system components other than pipelines are modeled as lognormally-distributed functions that give the probability of reaching or exceeding different damage states for a given level of ground motion (quantified in terms of PGA) and ground failure (quantified in terms of PGD). Each of these fragility curves is characterized by a median value of ground motion (or failure) and an associated dispersion factor (lognormal standard deviation). For oil piplines, empirical relations that give the expected repair rates due to ground motion (quantified in terms of PGV) or ground failure (quantified in terms of PGD) are provided.

Definitions of various damage states and the methodology used in deriving all these fragility curves are presented in the next section.

### 8.3.5 Description of Oil System Components

As mentioned before, an oil system typically consists of refineries, pumping plants, tank farms, and pipelines. In this section, a brief description of each of these components is given.

**Refineries (RF)**

Refineries are an important part of an oil system. They are used for processing crude oil before it can be used. Although supply of water is critical to the functioning of refinery, it is assumed in the methodology that an uninterrupted supply of water is available to the refinery. Two sizes of refineries are considered: small, and medium/large.

Small refineries (capacity less than 100,000 barrels per day), are assumed to consist of steel tanks on grade, stacks, other electrical and mechanical equipment, and elevated pipes. Stacks are essentially tall cylindrical chimneys.

Medium/Large refineries (capacity more than 100,000 barrels per day), are simulated by adding more redundancy to small refineries (i.e. twice as many tanks, stacks, elevated pipes).

**Oil Pipelines**

Oil pipelines are used for the transportation of oil over long distances. About seventy-five percent of the crude oil is transported throughout the United States by pipelines. A large segment of industry and millions of people could be severely affected by disruption of crude oil supplies. Rupture of crude oil pipelines could lead to pollution of land and rivers. Pipelines are typically made of mild steel with submerged arc welded joints, although older gas welded steel pipe may be present in some systems. In this sudy, buried pipelines are considered to be vulnerable to PGV and PGD.

**Pumping Plants (PP)**

Pumping plants serve to maintain the flow of oil in cross-country pipelines. Pumping plants usually use two or more pumps. Pumps can be of either centrifugal or reciprocating type. However, no differentiation is made between these two types of pumps in the analysis of oil systems. Pumping plants are classified as having either anchored or unanchored subcomponents, as defined in 7.2.5.

**Tank Farms (TF)**

Tank farms are facilities that store fuel products. They include tanks, pipes and electric components. Tank farms are classified as having either anchored or unanchored subcomponents, as defined in 7.2.5.

### 8.3.6 Definitions of Damage States

Oil systems are susceptible to earthquake damage. Facilities such as refineries, pumping plants and tank farms are mostly vulnerable to PGA, and sometimes PGD, if located in liquefiable or landslide zones. Therefore, the damage states for these components are defined and associated with PGA and PGD. Pipelines, on the other hand, are vulnerable to PGV and PGD. Therefore, the damage states for these components are associated with these two ground motion parameters.

#### 8.3.6.1 Damage States Definitions for Components other than Pipelines

A total of five damage states are defined for oil system components other than pipelines. These are none ($ds_1$), slight/minor ($ds_2$), moderate ($ds_3$), extensive ($ds_4$) and complete ($ds_5$).

**Slight/Minor Damage ($ds_2$)**

- **For refineries**, $ds_2$ is defined by malfunction of plant for a short time (few days) due to loss of electric power and backup power, if any, or light damage to tanks.

- **For pumping plants**, $ds_2$ is defined by light damage to building.

- **For tank farms**, $ds_2$ is defined by malfunction of plant for a short time (less than three days) due to loss of backup power or light damage to tanks.

**Moderate Damage ($ds_3$)**

- **For refineries**, $ds_3$ is defined by malfunction of plant for a week or so due to loss of electric power and backup power if any, extensive damage to various equipment, or considerable damage to tanks.

- **For pumping plants**, $ds_3$ is defined by considerable damage to mechanical and electrical equipment, or considerable damage to building.

- **For tank farms**, $ds_3$ is defined by malfunction of tank farm for a week or so due to loss of backup power, extensive damage to various equipment, or considerable damage to tanks.

**Extensive Damage ($ds_4$)**

- **For refineries**, $ds_4$ is defined by the tanks being extensively damaged, or stacks collapsing.

- **For pumping plants**, $ds_4$ is defined by the building being extensively damaged, or pumps badly damaged.

- **For tank farms**, $ds_4$ is defined by the tanks being extensively damaged, or extensive damage to elevated pipes.

**Complete Damage ($ds_5$)**

- **For refineries**, $ds_5$ is defined by the complete failure of all elevated pipes, or collapse of tanks.

- **For pumping plants**, $ds_5$ is defined by the building being in complete damage state.

- **For tank farms**, $ds_5$ is defined by the complete failure of all elevated pipes, or collapse of tanks.

### 8.3.6.2 Damage State Definitions for Pipelines

For pipelines, two damage states are considered. These are leaks and breaks. Generally, when a pipe is damaged due to ground failure, the type of damage is likely to be a break, while when a pipe is damaged due to seismic wave propagation; the type of damage is likely to be local buckling of the pipe walll. In the loss methodology, it is assumed that damage due to seismic waves will consist of 80% leaks and 20% breaks, while damage due to ground failure will consist of 20% leaks and 80% breaks. The user can override these default percentages.

### 8.3.7 Component Restoration Curves

The restoration curves for the oil system are obtained using the data for mean restoration time from ATC-13. The restoration functions for pumping plants are similar to those of pumping plants in potable water system. The data for refineries and tank farms are based on SF-18b and SF-18d of ATC-13. Means and standard deviations of the restoration functions are given in Table 8.17.a. The restoration functions are shown in Figures 8.32 through 8.34. Figure 8.32 represents the restoration functions for refineries, Figure 8.33 represents the restoration curves for tank farms, and Figure 8.34 represents the restoration curves for buried pipes. The discretized restoration functions are presented in Table 8.17.b, where the restoration percentage is given at discretized times. Restoration functions for oil pipelines are assumed to be the same as those for potable water pipelines.

**Table 8.17.a: Restoration Functions for Oil System Components**

| Restoration Functions (All Normal Distributions) | | | |
|---|---|---|---|
| **Classification** | **Damage State** | **Mean (Days)** | **σ** |
| Refineries | slight/minor | 0.4 | 0.1 |
| | moderate | 3.0 | 2.2 |
| | extensive | 14.0 | 12.0 |
| | complete | 190.0 | 80.0 |
| Tank Farms | slight/minor | 0.9 | 0.5 |
| | moderate | 7.0 | 7.0 |
| | extensive | 28.0 | 26.0 |
| | complete | 70.0 | 55.0 |
| Pipelines | leak | 3.0 | 2.0 |
| | break | 7.0 | 4.0 |

**Table 8.17.b: Discretized Restoration Functions for Oil System Components**

| Discretized Restoration Functions | | | | | | |
|---|---|---|---|---|---|---|
| **Classification** | **Damage State** | **1 day** | **3 days** | **7 days** | **30 days** | **90 days** |
| Refineries | slight/minor | 100 | 100 | 100 | 100 | 100 |
| | moderate | 19 | 50 | 97 | 100 | 100 |
| | extensive | 14 | 18 | 28 | 91 | 100 |
| | complete | 0 | 1 | 2 | 3 | 11 |
| Tank Farms | slight/minor | 58 | 100 | 100 | 100 | 100 |
| | moderate | 20 | 29 | 50 | 100 | 100 |
| | extensive | 15 | 17 | 21 | 54 | 100 |
| | complete | 11 | 12 | 13 | 24 | 65 |
| Pipelines | leak | 16 | 50 | 98 | 100 | 100 |
| | break | 7 | 16 | 50 | 100 | 100 |

### 8.3.8 Development of Damage Functions

In this subsection, damage functions for the various components of a refined or a crude oil system are presented. In cases where the components are made of subcomponents (i.e., refineries, tank farms and pumping plants), fragility curves for these components are based on the probabilistic combination of subcomponent damage functions using Boolean expressions to describe the relationship of subcomponents. It should be mentioned that the Boolean logic is implicitly presented within the definition of a particular damage state (see section 8.1.8 for an example).

It should be mentioned that damage functions due to ground failure (i.e., PGD) for refineries, tank farms and pumping plants are assumed to be similar to those described for potable water system facilities in section 8.1.8.

**Damage Functions for Refineries (due to Ground Shaking)**

PGA related damage functions for refineries are developed with respect to classification. Tables 8.18.a and 8.18.b present damage functions for small and medium/large refineries, respectively. These fragility curves are also plotted in Figures 8.35 through 8.38. The medians and dispersions of damage functions to refinery subcomponents are summarized in Tables C.8.1 and C.8.2 of Appendix 8C.

**Table 8.18.a: Damage Algorithms for Small Refineries (Capacity < 100,000 barrels/day)**

| Peak Ground Acceleration | | | |
|---|---|---|---|
| **Classification** | **Damage State** | **Median (g)** | **β** |
| Refineries with anchored components (ORF1) | slight/minor | 0.29 | 0.55 |
| | moderate | 0.52 | 0.50 |
| | extensive | 0.64 | 0.60 |
| | complete | 0.86 | 0.55 |
| Refineries with unanchored components (ORF2) | slight/minor | 0.13 | 0.50 |
| | moderate | 0.27 | 0.50 |
| | extensive | 0.43 | 0.60 |
| | complete | 0.68 | 0.55 |

**Table 8.18.b: Damage Algorithms for Medium/Large Refineries (Capacity ≥ 100,000 barrels/day)**

| Peak Ground Acceleration | | | |
|---|---|---|---|
| **Classification** | **Damage State** | **Median (g)** | **β** |
| Refineries with anchored components (ORF3) | slight/minor | 0.38 | 0.45 |
| | moderate | 0.60 | 0.45 |
| | extensive | 0.98 | 0.50 |
| | complete | 1.26 | 0.45 |
| Refineries with unanchored components (ORF4) | slight/minor | 0.17 | 0.40 |
| | moderate | 0.32 | 0.45 |
| | extensive | 0.68 | 0.50 |
| | complete | 1.04 | 0.45 |

**Damage Functions for Pumping Plants (due to Ground Shaking)**

PGA related damage functions for pumping plants are also developed with respect to classification and ground motion parameter and are presented in Table 8.19. These damage functions are also plotted in Figures 8.39 and 8.40. The medians and dispersions of pumping plants subcomponent damage functions are summarized in Tables C.8.3 and C.8.4 of Appendix 8C.

**Table 8.19: Damage Algorithms for Pumping Plants**

| Peak Ground Acceleration | | | |
|---|---|---|---|
| **Classification** | **Damage State** | **Median (g)** | **β** |
| Plants with anchored components (OPP1) | slight/minor | 0.15 | 0.75 |
| | moderate | 0.34 | 0.65 |
| | extensive | 0.77 | 0.65 |
| | complete | 1.50 | 0.80 |
| Plants with unanchored components (OPP2) | slight/minor | 0.12 | 0.60 |
| | moderate | 0.24 | 0.60 |
| | extensive | 0.77 | 0.65 |
| | complete | 1.50 | 0.80 |

**Damage Functions for Tank Farms (due to Ground Shaking)**

PGA related damage functions for tank farms are developed with respect to classification and ground motion parameter. These damage functions are given in terms of median values and dispersions corresponding each damage state in Table 8.20. The fragility curves are plotted in Figures 8.41 and 8.42. The medians and dispersions of tank farms subcomponent damage functions are presnted in Appendix 8C.

**Table 8.20: Damage Algorithms for Tank Farms**

| Peak Ground Acceleration | | | |
|---|---|---|---|
| **Classification** | **Damage State** | **Median (g)** | **β** |
| Plants with anchored components (OTF1) | slight/minor | 0.29 | 0.55 |
| | moderate extensive | 0.50 | 0.55 |
| | complete | 0.87 | 0.50 |
| Plants with unanchored components (OTF2) | slight/minor | 0.12 | 0.55 |
| | moderate | 0.23 | 0.55 |
| | extensive | 0.41 | 0.55 |
| | complete | 0.68 | 0.55 |

**Damage Functions for Oil Pipelines**

The same two damage algorithms proposed for potable water pipelines are assumed to apply for crude and refined oil pipelines. These are listed again in Table 8.21. Note that mild steel pipelines with submerged arc welded joints are classfied as ductile pipes, while the older gas welded steel pipelines, if any, are classifed as brittle pipes. In Table 8.21, R.R. stands for repair rates or number of repairs per kilometer, PGV stands for peak ground velocity in cm/sec, and PGD stands for permanent ground deformation in inches.

**Table 8.21: Damage Algorithms for Oil Pipelines**

| | **PGV Algorithm** | | **PGD Algorithm** | |
|---|---|---|---|---|
| | R. R. $\cong$ 0.0001 x PGV$^{(2.25)}$ | | R. R. $\cong$ Prob[liq]xPGD$^{(0.56)}$ | |
| **Pipe Type** | Multiplier | Example of Pipe | Multiplier | Example of Pipe |
| Brittle Oil Pipelines (OIP1) | 1 | Steel Pipe w/ GasWJ | 1 | Steel Pipe w/ GasWJ |
| Ductile Oil Pipelines (OIP2) | 0.3 | Steel Pipe w/ ArcWJ | 0.3 | Steel Pipe w/ ArcWJ |

## 8.3.9 Guidance for Loss Estimation with Advanced Data and Models

For this type of analysis, the expert can use the methodology developed with the flexibility to (1) include a more refined inventory of the oil system pertaining to the area of study, and (2) include component-specific and system-specific fragility data. Default damage algorithms for User-Supplied Data Analysis, can be modified or replaced to incorporate improved information about key components of an oil system. Similarly, better restoration curves can be developed, given knowledge of available resources.

## 8.3.10 References

(1) ATC-13, "Earthquake Damage Evaluation Data for California", Applied Technology Council, Redwood City, CA, 1985.

(2) G&E Engineering Systems, Inc. (G&E), "NIBS Earthquake Loss Estimation Methods, Technical Manual, (Fuel Systems)", June 1994.

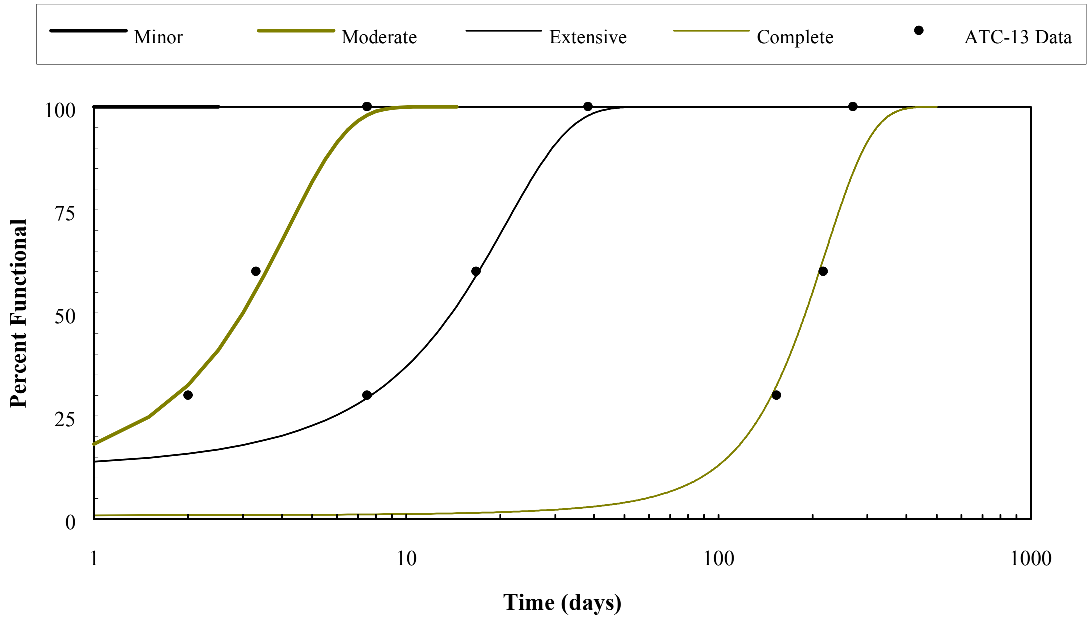


**Figure 8.32: Restoration Curves for Refineries.**

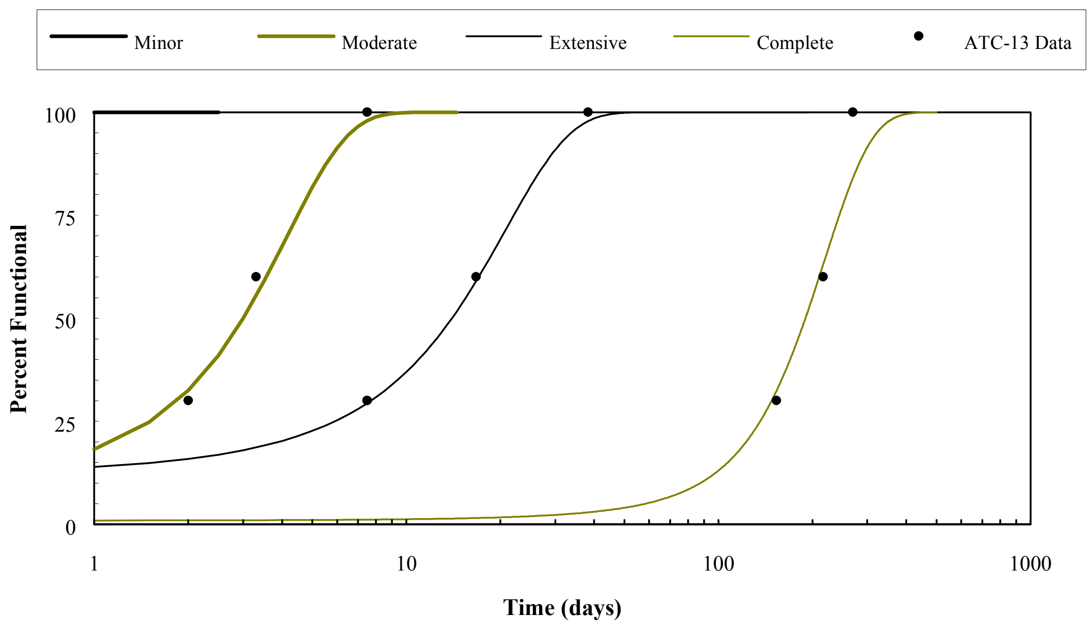


**Figure 8.33: Restoration Curves for Tank Farms.**

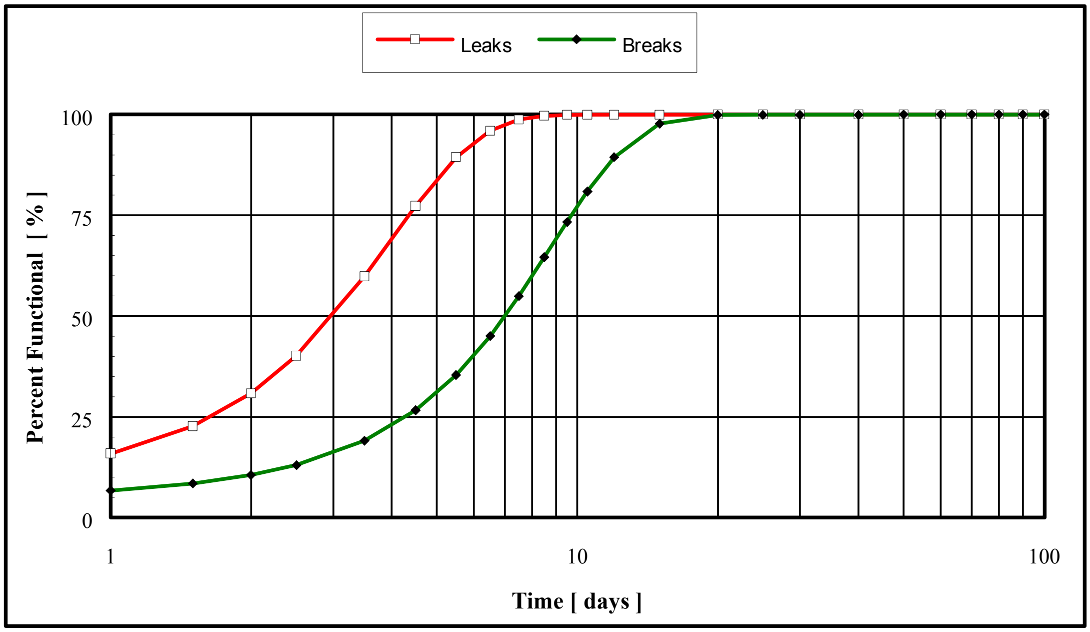


**Figure 8.34: Restoration Curves for Oil Pipelines.**

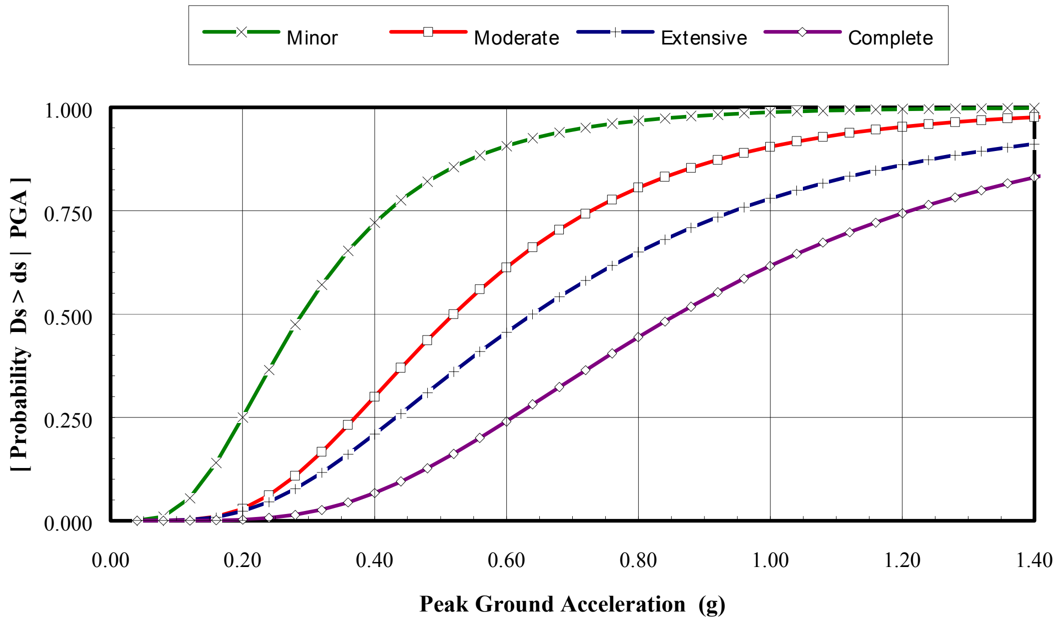


**Figure 8.35: Fragility Curves for Small Refineries with Anchored Components.**

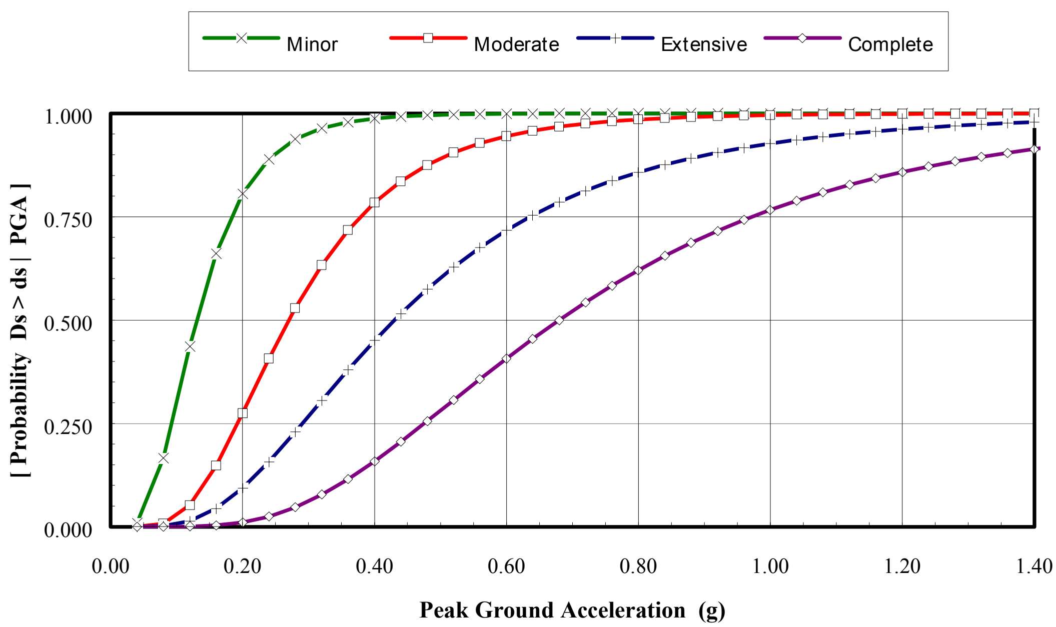


**Figure 8.36: Fragility Curves for Small Refineries with Unanchored Components.**

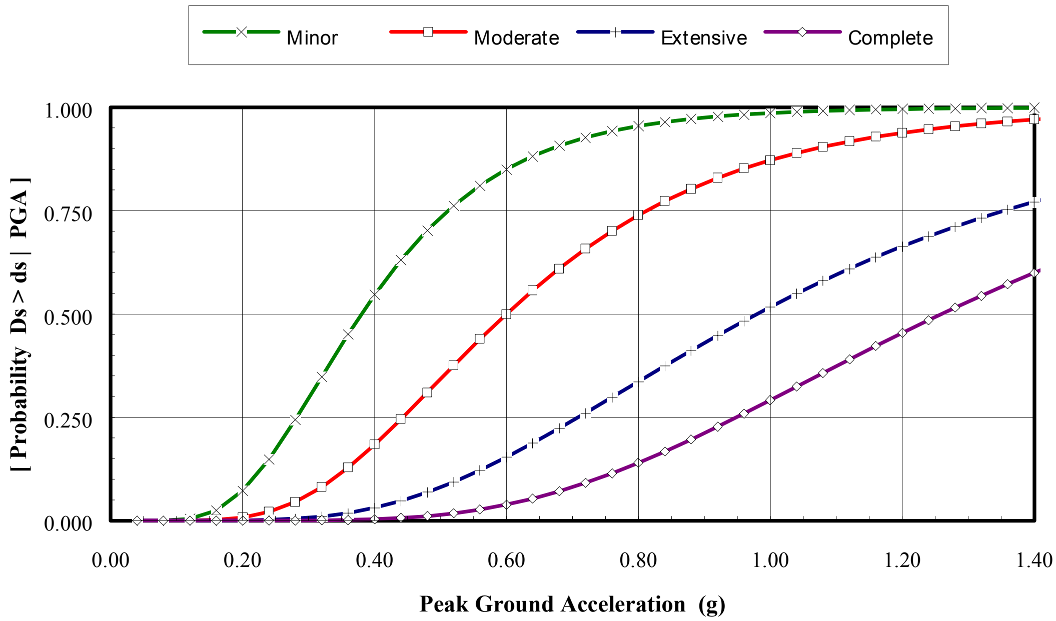


**Figure 8.37:  Fragility Curves for Medium/Large Refineries with Anchored Components.**

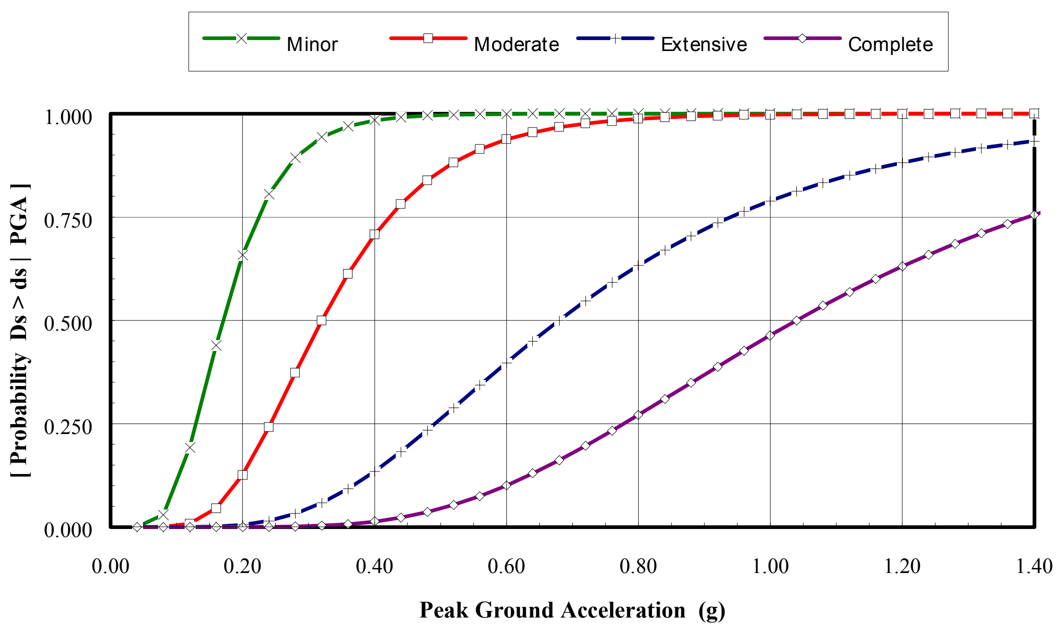


**Figure 8.38:  Fragility Curves for Medium/Large Refineries with Unanchored Components.**

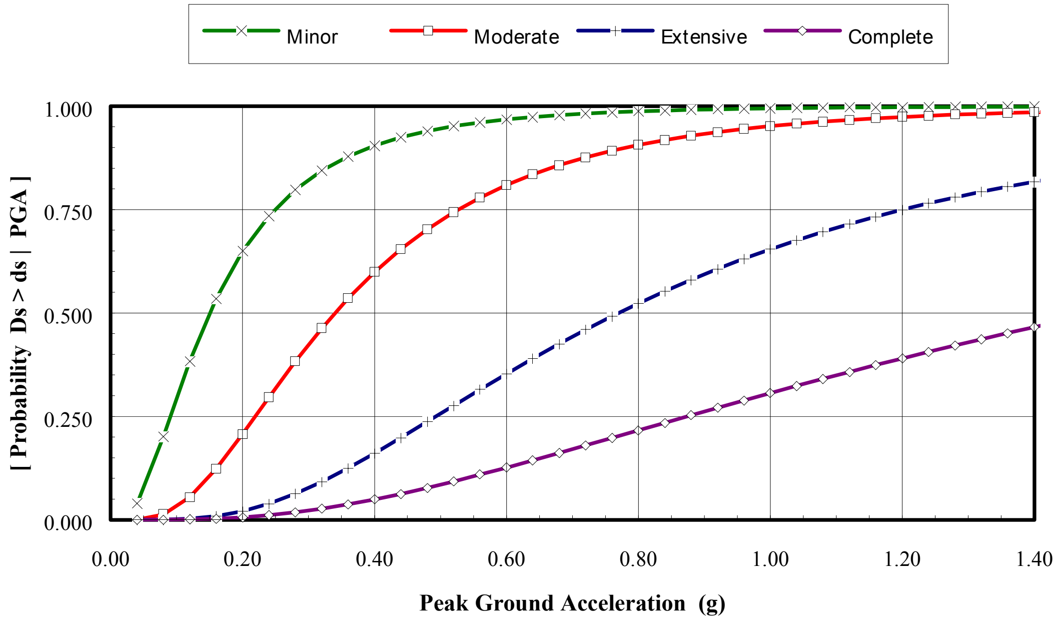


**Figure 8.39: Fragility Curves for Pumping Plants with Anchored Components.**

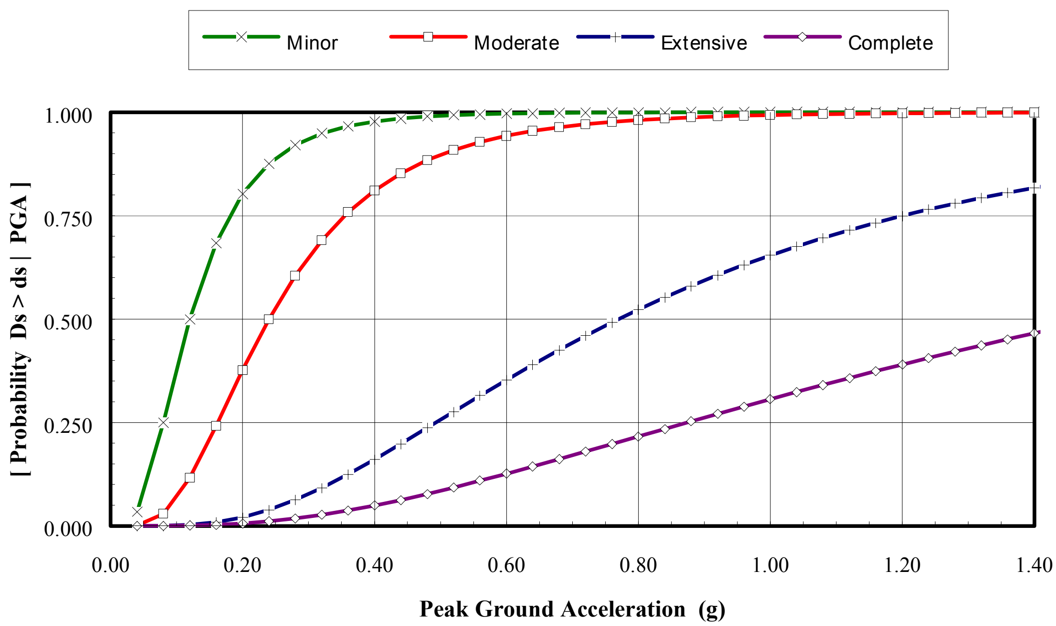


**Figure 8.40: Fragility Curves for Pumping Plants with Unanchored Components.**

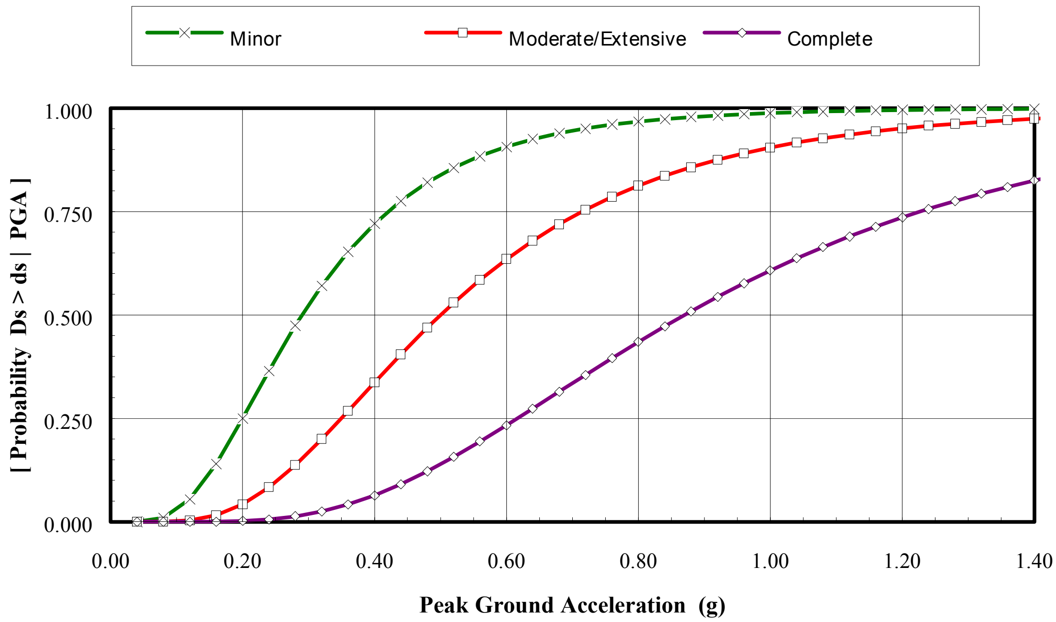


**Figure 8.41: Fragility Curves for Tank Farms with Anchored Components.**

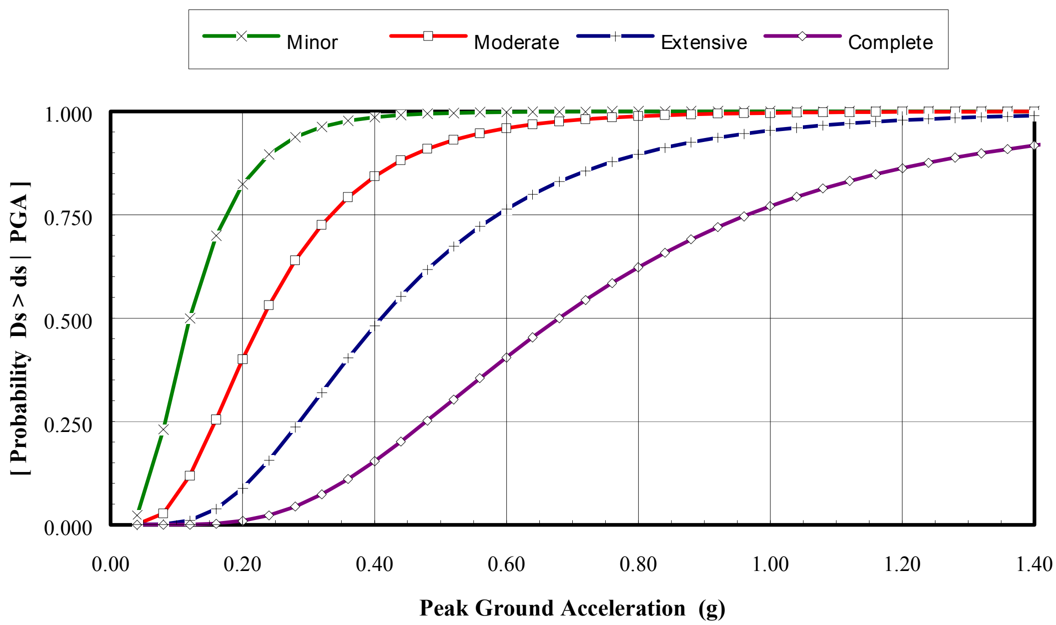


**Figure 8.42: Fragility Curves for Tank Farms with Unanchored Components.**

## 8.4 Natural Gas Systems

### 8.4.1 Introduction

A natural gas system consists of compressor stations and buried/elevated pipelines. Both of these components are vulnerable to damage during earthquakes. In addition to economic losses, failure of natural gas systems can also cause fires.

### 8.4.2 Scope

The scope of this section includes development of methods for estimation of earthquake damage to a natural gas system given knowledge of components (i.e. compressor stations), classification (i.e. for compressor stations, with anchored or unanchored components), and ground motion (i.e. peak ground velocity, peak ground acceleration and/or permanent ground deformation). Damage states describing the level of damage to each of the natural gas system components are defined (i.e., minor, moderate, extensive or complete for facilities and number of repairs/km for pipelines). Fragility curves are developed for each classification of the natural gas system component. These curves describe the probability of reaching or exceeding each damage state given the level of ground motion (or ground failure). Based on these fragility curves, functionality of each component of the natural gas system can be assessed.

### 8.4.3 Input Requirements and Output Information

Required input to estimate damage to natural gas systems are described below.

**Compressor Stations**

- Geographic location of facility (longitude and latitude)
- PGA and PGD
- Classification (w/ or w/o anchored components)

**Natural Gas Pipelines**

- Geographic location of pipeline links (longitude and latitude of end nodes)
- PGV and PGD
- Classification

Direct damage output for natural gas systems includes probability estimates of (1) component functionality and (2) damage, expressed in terms of the component's damage ratio (repair cost to replacement cost). Note that damage ratios for each of the natural gas system components are presented in section 15.3 of Chapter 15.

### 8.4.4 Form of Damage Functions

Damage functions or fragility curves for natural gas system components mentioned above are lognormally distributed functions that give the probability of reaching or exceeding different levels of damage for a given level of ground motion.

- For compressor stations, these fragility curves are defined by a median PGA/PGD and a dispersion.

- For natural gas pipelines, these fragility curves are defined by a median PGV/PGD and dispersion.

Definitions of various damage states and the methodology used in deriving all these fragility curves are presented in the next section.

### 8.4.5 Description of Natural Gas System Components

As mentioned before, a natural gas system typically consists of compressor stations and pipelines. In this section, a brief description of each of these components is given.

**Compressor Stations**

Compressor stations serve to maintain the flow of gas in cross-country pipelines. Compressor stations consist of either centrifugal or reciprocating compressors. However, no differentiation is made between these two types of compressors in the analysis of natural gas systems. Compressor stations are categorized as having either anchored or unanchored subcomponents, as defined in 7.2.5. The compressor stations are similar to pumping plants in oil systems discussed in Section 8.3.

**Natural Gas Pipelines**

Pipelines are typically made of mild steel with submerged arc welded joints, although older lines may have gas-welded joints. These are used for the transportation of natural gas over long distances. Many industries and residents could be severely affected should disruption of natural gas supplies occur.

### 8.4.6 Definitions of Damage States

Facilities such as compressor stations are mostly vulnerable to PGA, sometimes PGD, if located in liquefiable or landslide zones. Therefore, damage states for these components are defined and associated with either PGA or PGD. Pipelines, on the other hand, are vulnerable to PGV and PGD; therefore, damage states for these components are associated with these two ground motion parameters.

#### 8.4.6.1 Damage States Definitions for Compressor Stations

A total of five damage states are defined for gas system components. These are none ($ds_1$), slight/minor ($ds_2$), moderate ($ds_3$), extensive ($ds_4$) and complete ($ds_5$).

**Slight/Minor Damage ($ds_2$)**

- $ds_2$ is defined by slight damage to building.

**Moderate Damage ($ds_3$)**

- $ds_3$ is defined by considerable damage to mechanical and electrical equipment, or considerable damage to building.

**Extensive Damage ($ds_4$)**

- $ds_4$ is defined by the building being extensively damaged, or the pumps badly damaged beyond repair.

**Complete Damage ($ds_5$)**

- $ds_5$ is defined by the building in complete damage state.

#### 8.4.6.2 Damage States Defintions for Pipelines

For pipelines, two damage states are considered. These are leaks and breaks. Generally, when a pipe is damaged due to ground failure, the type of damage is likely to be a break, while when a pipe is damaged due to seismic wave propagation; the type of damage is likely to be local bucking of the pipe wall. In the loss methodology, it is assumed that damage due to seismic waves will consist of 80% leaks and 20% breaks, while damage due to ground failure will consist of 20% leaks and 80% breaks. The user can override these default percentages.

### 8.4.7 Component Restoration Curves

The restoration curves for natural gas system components are similar to those of the oil system discussed in Section 8.3.7. Compressor stations in natural gas systems are analogous to pumping plants in oil systems.

### 8.4.8 Development of Damage Functions

Fragility curves for natural gas system components are defined with respect to classification and ground motion parameter.

**Damage Functions for Compressor Stations**

Damage functions for compressor stations are taken as identical to those of pumping plants in oil systems discussed in Section 8.3.8.

**Damage Functions for Pipelines**

Damage functions for natural gas pipelines are taken as identical to those for oil pipelines discussed in Section 8.3.8.

### 8.4.9 Guidance for Loss Estimation with Advanced Data and Models Analysis

For this type of analysis, the expert can use the methodology developed with the flexibility to (1) include a more refined inventory of the natural gas system pertaining to the area of study, and (2) include component-specific and system-specific fragility data. Default damage algorithms for User-Supplied Data Analysis can be modified or replaced to incorporate improved information about key components of a natural system. Similarly, better restoration curves can be developed, given knowledge of available resources.

### 8.4.10 References

(1) ATC-13, "Earthquake Damage Evaluation Data for California", Applied Technology Council, Redwood City, CA, 1985.

(2) G&E Engineering Systems, Inc. (G&E), "NIBS Earthquake Loss Estimation Methods, Technical Manual, (Fuel Systems)", June 1994.

## 8.5 Electric Power Systems

### 8.5.1 Introduction

This section presents the earthquake loss estimation methodology for an electric power system. This system consists of generation facilities, substations, and distribution circuits. All of these components are vulnerable to damage during earthquakes, which may result in significant disruption of power supply.

### 8.5.2 Scope

The scope of this section includes development of methods for estimating earthquake damage to an electric power system given knowledge of components (i.e. generation facilities, substations, and distribution circuits), classification (i.e., for substations, low voltage, medium voltage, or high voltage), and the ground motion (i.e. peak ground acceleration and permanent ground deformation). Damage states describing the level of damage to each of the electric power system components are defined (i.e., minor, moderate, extensive or complete). Fragility curves are developed for each classification of the electric power system component. These curves describe the probability of reaching or exceeding each damage state given the level of ground motion.

Based on these fragility curves, the method for assessing functionality of each component of the electric power system is presented.

### 8.5.3 Input Requirements and Output Information

Required input to estimate damage to electric power systems includes the following items:

**Substations**

- Longitude and latitude of facility
- PGA and PGD
- Classification (low, medium, or high voltage; with anchored or standard components)

**Distribution Circuits**

- Longitude and latitude of facility
- PGA
- Classification (seismically designed or standard components)

**Generation Plants**

- Longitude and latitude of facility
- PGA

- Classification (small or medium/large, with anchored or unanchored components)

Direct damage output for an electric power system includes probability estimates of (1) component functionality and (2) damage, expressed in terms of the component's damage ratio. Damage ratios for electric power systems components are presented in section 15.3 of Chapter 15. A simplified system performance evaluation methodology is also provided. The output from this simplified version of system analysis consists of a probabilistic estimate for the power outage.

### 8.5.4 Form of Damage Functions

Damage functions or fragility curves for all electric power system components mentioned above are modeled as lognormally-distributed functions that give the probability of reaching or exceeding different levels of damage for a given level of ground motion. These fragility curves are defined by a median ground motion parameter and a dispersion.

### 8.5.5 Description of Electric Power System Components

As mentioned before, the components of an electric power system considered in the loss estimation methodology are substations, distribution circuits, and generation plants. In this section a brief description of each of these components is presented.

**Substations**

An electric substation is a facility that serves as a source of energy supply for the local distribution area in which it is located, and has the following main functions:

- Change or switch voltage from one level to another.
- Provide points where safety devices such as disconnect switches, circuit breakers, and other equipment can be installed.
- Regulate voltage to compensate for system voltage changes.
- Eliminate lightnning and switching surges from the system.
- Convert AC to DC and DC to AC, as needed.
- Change frequency, as needed.

Substations can be entirely enclosed in buildings where all the equipment is assembled into one metal clad unit. Other substations have step-down transformers, high voltage switches, oil circuit breakers, and lightning arrestors located outside the substation building. In the current loss estimation methodology, only transmission (138 kV to 765 kV or higher) and subtransmission (34.5 kV to 161 kV) substations are considered. These will be classified as high voltage (350 kV and above), medium voltage (150 kV to 350 kV) and low voltage (34.5 kV to 150 kV), and will be referred to as 500 kV substations, 230kV substations, and 115kV substations, respectively. The classification is also a function of whether the subcomponents are anchored or typical (unanchored), as defined in 7.2.5.

**Distribution Circuits**

The distribution system is divided into a number of circuits. A distribution circuit includes poles, wires, in-line equipment and utility-owned equipment at customer sites. A distribution circuit also includes above ground and underground conductors. Distribution circuits either consist of anchored or unanchored components.

**Generation Plants**

These plants produce alternating current (AC) and may be any of the following types:

- Hydroelectric
- Steam turbine (fossil fuel fired or nuclear)
- Combustion turbine (fossil fuel fired)
- Geothermal
- Solar
- Wind
- Compressed air

Fossil fuels are either coal, oil, or natural gas.
Generation plant subcomponents include diesel generators, turbines, racks and panels, boilers and pressure vessels, and the building in which these are housed.

The size of the generation plant is determined from the number of Megawatts of electric power that the plant can produce under normal operations. Small generation plants have a generation capacity of less than 200 Megawatts. Medium/Large generation plants have a capacity greater than 200 Megawatts. Fragility curves for generation plants with anchored versus unanchored subcomponents are presented.

### 8.5.6 Definitions of Damage States

Electric power systems are susceptible to earthquake damage. Facilities such as substations, generation plants, and distribution circuits are mostly vulnerable to PGA, and sometimes PGD, if located in liquefiable or landslide zones. Therefore, the damage states for these components are defined in terms of PGA and PGD.

A total of five damage states are defined for electric power system components. These are none ($ds_1$), slight/minor ($ds_2$), moderate ($ds_3$), extensive ($ds_4$) and complete ($ds_5$).

Note that for power systems, in particular for substations and distribution circuits, these damage states are defined with respect to the percentage of subcomponents being damaged. That is, for a substation with $n_1$ transformers, $n_2$ disconnect switches, $n_3$ circuit breakers, and $n_4$ current transformers, the substation is said to be in a slight or minor damage state if 5% of $n_2$ or 5% of $n_3$ are damaged, and it is in the extensive damage state if 70% of $n_1$, 70% of $n_2$, or 70% of $n_3$ are damaged, or if the building is in extensive damage state. A parametric study on $n_1$, $n_2$, $n_3$, and $n_4$ values shows that the medians of the damage states defined in this manner don't change appreciably (less than 3 %) as the $n_i$'s vary, while the corresponding dispersions get smaller as the $n_i$'s increase. Therefore, we used dispersions obtained from the small sample numbers along with the relatively constant median values.

**Slight/Minor Damage ($ds_2$)**

- For substations, $ds_2$ is defined as the failure of 5% of the disconnect switches (i.e., misalignment), or the failure of 5 % of the circuit breakers (i.e., circuit breaker phase sliding off its pad, circuit breaker tipping over, or interrupter-head falling to the ground), or by the building being in minor damage state.

- For distribution circuits, $ds_2$ is defined by the failure of 4 % of all circuits.

- For generation plants, $ds_2$ is defined by turbine tripping, or light damage to diesel generator, or by the building being in minor damage state.

**Moderate Damage ($ds_3$)**

- For substations, $ds_3$ is defined as the failure of 40% of disconnect switches (e.g., misalignment), or 40% of circuit breakers (e.g., circuit breaker phase sliding off its pad, circuit breaker tipping over, or interrupter-head falling to the ground), or failure of 40% of current transformers (e.g., oil leaking from transformers, porcelain cracked), or by the building being in moderate damage state.

- For distribution circuits, $ds_3$ is defined by the failure of 12% of circuits.

- For generation plants, $ds_3$ is defined some by the chattering of instrument panels and racks, considerable damage to boilers and pressure vessels, or by the building being in moderate damage state.

**Extensive Damage ($ds_4$)**

- For substations, $ds_4$ is defined as the failure of 70% of disconnect switches (e.g., misalignment), 70% of circuit breakers, 70% of current transformers (e.g., oil leaking from transformers, porcelain cracked), or by failure of 70% of transformers (e.g., leakage of transformer radiators), or by the building being in extensive damage state.

- For distribution circuits, $ds_4$ is defined by the failure of 50% of all circuits.

- For generation plants, $ds_4$ is defined by considerable damage to motor driven pumps, or considerable damage to large vertical pumps, or by the building being in extensive damage state.

**Complete Damage ($ds_5$)**

- For substations, $ds_5$ is defined as the failure of all disconnect switches, all circuit breakers, all transformers, or all current transformers, or by the building being in complete damage state.
- For distribution circuits, $ds_5$ is defined by the failure of 80% of all circuits.
- For generation plants, $ds_5$ is defined by extensive damage to large horizontal vessels beyond repair, extensive damage to large motor operated valves, or by the building being in complete damage state.

### 8.5.7 Component Restoration Curves

Restoration curves for electric substations and distribution circuits are based on a G&E report (1994), while restoration curves for generation facilities are obtained using the data for mean restoration times from ATC-13 social function SF-29.a (the first four damage states). These functions are presented in Tables 8.22.a and 8.22.b. The first table gives means and standard deviations for each restoration curve (i.e., smooth continuous curve), while the second table gives approximate discrete functions for the restoration curves developed. These restoration functions are also shown in Figures 8.43 through 8.45.

**Table 8.22.a: Restoration Functions for Electric Power System Components**

| Restoration Functions (All Normal Distributions) | | | |
|---|---|---|---|
| **Classification** | **Damage State** | **Mean (Days)** | **$\beta$** |
| Electric Sub-Stations | slight/minor | 1.0 | 0.5 |
| | moderate | 3.0 | 1.5 |
| | extensive | 7.0 | 3.5 |
| | complete | 30.0 | 15.0 |
| Distribution Circuits | slight/minor | 0.3 | 0.2 |
| | moderate | 1.0 | 0.5 |
| | extensive | 3.0 | 1.5 |
| | complete | 7.0 | 3.0 |
| Generation Facilities | slight/minor | 0.5 | 0.1 |
| | moderate | 3.6 | 3.6 |
| | extensive | 22.0 | 21.0 |
| | complete | 65.0 | 30.0 |

**Table 8.22.b: Discretized Restoration Functions for Electric Power Components**

| Discretized Restoration Functions | | | | | | |
|---|---|---|---|---|---|---|
| **Classification** | **Damage State** | **1 day** | **3 days** | **7 days** | **30 days** | **90 days** |
| Electric Sub-Stations | slight/minor | 50 | 100 | 100 | 100 | 100 |
| | moderate | 9 | 50 | 100 | 100 | 100 |
| | extensive | 4 | 13 | 50 | 100 | 100 |
| | complete | 3 | 4 | 7 | 50 | 100 |
| Distribution Circuits | slight/minor | 100 | 100 | 100 | 100 | 100 |
| | moderate | 50 | 100 | 100 | 100 | 100 |
| | extensive | 9 | 50 | 100 | 100 | 100 |
| | complete | 2 | 10 | 50 | 100 | 100 |
| Generation Facilities | slight/minor | 100 | 100 | 100 | 100 | 100 |
| | moderate | 24 | 44 | 83 | 100 | 100 |
| | extensive | 16 | 19 | 24 | 65 | 100 |
| | complete | 2 | 2 | 3 | 13 | 80 |

## 8.5.8 Development of Damage Functions

Fragility curves for electric power system components are defined with respect to classification and ground motion parameters. These curves are based on the probabilistic combination of subcomponent damage functions using Boolean expressions to describe the relationship of subcomponents. The Boolean approach involves evaluation of the probability of each component reaching or exceeding different damage states, as defined by the damage level of its subcomponents. It should be mentioned that the Boolean logic is implicitly presented within the definition of a particular damage state. For example, the moderate damage state for substations is defined as the failure of 40% of disconnect switches, OR the failure of 40% of circuit breakers, OR the failure of 40% of transformers, OR by the building being in moderate damage state. Therefore, the fault tree for moderate damage for substations has FOUR primary OR branches: disconnect switches, circuit breakers, transformers, and building. Within the first 3 OR branches (i.e., disconnect switches, circuit breakers, and transformers) the multiple possible combinations are considered. These evaluations produce component probabilities at various levels of ground motion. In general, the Boolean combinations do not produce a lognormal distribution, so a lognormal curve that best fits this probability distribution is determined numerically.

Damage functions due to ground failure (i.e., PGD) for substations and generation plants are assumed to be similar to those described for potable water system facilities in section 8.1.8.

### PGA Related Damage Functions for Electric Power Substations

A total of 24 sub-station damage functions are used in the methodology. Half of these damage functions correspond to substations with anchored components, while the other half correspond to substations with unanchored components.

Medians and dispersions of these damage functions are given in Tables 8.23 and 8.24. These damage functions are also presented in the form of fragility curves in Figures 8.46 through 8.51. Note that each figure contains four damage functions.

**Table 8.23: Damage Algorithms for Substations (Anchored / Seismic Components)**

| Peak Ground Acceleration | | | |
|---|---|---|---|
| **Classification** | **Damage State** | **Median (g)** | **β** |
| Low voltage (ESS1) | slight/minor | 0.15 | 0.70 |
| | moderate | 0.29 | 0.55 |
| | extensive | 0.45 | 0.45 |
| | complete | 0.90 | 0.45 |
| Medium voltage (ESS3) | slight/minor | 0.15 | 0.60 |
| | moderate | 0.25 | 0.50 |
| | extensive | 0.35 | 0.40 |
| | complete | 0.70 | 0.40 |
| High voltage (ESS5) | slight/minor | 0.11 | 0.50 |
| | moderate | 0.15 | 0.45 |
| | extensive | 0.20 | 0.35 |
| | complete | 0.47 | 0.40 |

**Table 8.24: Damage Algorithms for Substations (Unanchored / Standard Components)**

| Peak Ground Acceleration | | | |
|---|---|---|---|
| **Classification** | **Damage State** | **Median (g)** | **β** |
| Low voltage (ESS2) | slight/minor | 0.13 | 0.65 |
| | moderate | 0.26 | 0.50 |
| | extensive | 0.34 | 0.40 |
| | complete | 0.74 | 0.40 |
| Medium voltage (ESS4) | slight/minor | 0.10 | 0.60 |
| | moderate | 0.20 | 0.50 |
| | extensive | 0.30 | 0.40 |
| | complete | 0.50 | 0.40 |
| High voltage (ESS6) | slight/minor | 0.09 | 0.50 |
| | moderate | 0.13 | 0.40 |
| | extensive | 0.17 | 0.35 |
| | complete | 0.38 | 0.35 |

**PGA Related Damage Functions for Distribution Circuits**

A total of 8 distribution circuits damage functions are obtained. Four of these damage functions correspond to distribution circuits with seismically designed components, while the other four correspond to distribution circuits with standard components. Medians and dispersions of these damage functions are presented in Table 8.25 and plotted in Figures 8.52 and 8.53. Note that subcomponent damage functions of a distribution circuit are presented in Table D.8.7 of Appendix 8D.

**Table 8.25: Damage Algorithms for Distribution Circuits**

| Peak Ground Acceleration | | | |
|---|---|---|---|
| **Classification** | **Damage State** | **Median (g)** | **β** |
| Seismic Components (EDC1) | slight/minor | 0.28 | 0.30 |
| | moderate | 0.40 | 0.20 |
| | extensive | 0.72 | 0.15 |
| | complete | 1.10 | 0.15 |
| Standard Components (EDC2) | slight/minor | 0.24 | 0.25 |
| | moderate | 0.33 | 0.20 |
| | extensive | 0.58 | 0.15 |
| | complete | 0.89 | 0.15 |

## PGA Related Damage Functions for Generation Plants

A total of 16 damage functions for generation plants are developed. Eight of these damage functions correspond to small generation plants (less than 200 MW), while the other eight correspond to medium/large plants (more than 200 MW). Medians and dispersions of these damage functions are given in Tables 8.26 and 8.27. These damage functions are also shown as fragility curves in Figures 8.54 through 8.57. Note that subcomponent damage functions of a generation plant are presented in Tables D.8.8 and D.8.9 of Appendix 8D.

**Table 8.26: Damage Algorithms for Small Generation Facilities**

| Peak Ground Acceleration | | | |
|---|---|---|---|
| **Classification** | **Damage State** | **Median (g)** | **β** |
| Facility with Anchored Components (EPP1) | slight/minor | 0.10 | 0.55 |
| | moderate | 0.21 | 0.55 |
| | extensive | 0.48 | 0.50 |
| | complete | 0.78 | 0.50 |
| Facility with Unanchored Components (EPP2) | slight/minor | 0.10 | 0.50 |
| | moderate | 0.17 | 0.50 |
| | extensive | 0.42 | 0.50 |
| | complete | 0.58 | 0.55 |

**Table 8.27: Damage Algorithms for Medium/Large Generation Facilities**

| Peak Ground Acceleration | | | |
|---|---|---|---|
| **Classification** | **Damage State** | **Median (g)** | **β** |
| Facility with Anchored Components (EPP3) | slight/minor | 0.10 | 0.60 |
| | moderate | 0.25 | 0.60 |
| | extensive | 0.52 | 0.55 |
| | complete | 0.92 | 0.55 |
| Facility with Unanchored Components (EPP4) | slight/minor | 0.10 | 0.60 |
| | moderate | 0.22 | 0.55 |
| | extensive | 0.49 | 0.50 |
| | complete | 0.79 | 0.50 |

### 8.5.9 Power Outage and Performance Evaluation for Electric Power Systems

For electric power systems, power service outages for the study region are assumed to be dependent on the nonfunctionality of substations servicing the region. This component is in fact among one of the more vulnerable electric power component to earthquake, and damage to this facility affects wide areas.

**Example**

Assume that in a study region, in the Western US, there are 2 medium voltage substations, both with anchored designed components. At one facility the PGA is 0.15g while at the other facility the PGA is 0.3g. We want to evaluate the electric power system performance. The damage and restoration algorithms for medium voltage substations are reproduced in Table 8.28.

**Table 8.28: Electric Power System Performance Example Parameters**

| Medium Voltage Substations with Seismic Components | | |
|---|---|---|
| **Damage State** | **Median (g)** | **β** |
| slight/minor | 0.15 | 0.6 |
| moderate | 0.25 | 0.5 |
| extensive | 0.35 | 0.4 |
| complete | 0.7 | 0.4 |
| **Continuous Restoration Functions (All Normal Distributions)** | | |
| **Damage State** | **Mean (days)** | **σ (days)** |
| slight/minor | 1.0 | 0.5 |
| moderate | 3.0 | 1.5 |
| extensive | 7.0 | 3.5 |
| complete | 30 | 15 |

| Discretized Restoration Functions | | | | |
|---|---|---|---|---|
| **Damage State** | **3 days** | **7 days** | **30 days** | **90 days** |
| slight/minor | 100 | 100 | 100 | 100 |
| moderate | 50 | 100 | 100 | 100 |
| extensive | 13 | 50 | 100 | 100 |
| complete | 4 | 7 | 50 | 100 |

The discrete probabilities for different damage states are then determined at these two substations:

At Substation 1,

$$P[\,D_S = ds_1 \mid PGA = 0.15g\,] = 0.50$$
$$P[\,D_S = ds_2 \mid PGA = 0.15g\,] = 0.35$$
$$P[\,D_S = ds_3 \mid PGA = 0.15g\,] = 0.13$$
$$P[\,D_S = ds_4 \mid PGA = 0.15g\,] = 0.02$$
$$P[\,D_S = ds_5 \mid PGA = 0.15g\,] = 0.00$$

At substation 2,

$$P[\,D_S = ds_1 \mid PGA = 0.3g\,] = 0.12$$
$$P[\,D_S = ds_2 \mid PGA = 0.3g\,] = 0.24$$
$$P[\,D_S = ds_3 \mid PGA = 0.3g\,] = 0.29$$
$$P[\,D_S = ds_4 \mid PGA = 0.3g\,] = 0.33$$
$$P[\,D_S = ds_5 \mid PGA = 0.3g\,] = 0.02$$

The best estimate of functionality for each restoration period is estimated by the weighted combination:

$$FP_c = \sum_{i=1}^{i=5} FR_i \times P[ds_i]$$

In this example, the weighted combination after 3 days would be:

At substation # 1,

$FP_c$ [3 days] = 0.5 x 100% + 0.35 x 100% + 0.13 x 50% + 0.02 x 13% + 0.0 x 4%

= 91.8 %

At substation # 2,
$FP_C$ [3 days] = 0.12 x 100 %+ 0.24 x 100% + 0.29 x 50% + 0.33 x 13% + 0.02 x 4%
= 54.9 %

Therefore, in the study region and 3 days after the earthquake, about 8% of the area serviced by substation # 1 will be still suffering power outage while 45% of the area serviced by substation # 2 will be still out of power, or in average 23% of the whole study region will be out of power.

Note that the expected number of customers without power after each restoration period is estimated by multiplying the probability of power outage with the number of households (housing units) in each census tract.

Finally, it should be mentioned that the interaction between electric power and other lifeline systems was considered marginally through a fault tree analysis. Loss of electric power is assumed to affect only the slight/minor and moderate damage states of other lifeline systems that depend on power. This assumption is based on the fact that if a water treatment plant, for example, is in the extensive damage state that the availability of power becomes of secondary importance. The fault tree analysis also assumes that the substation serving the other lifeline components it interacts with will be subject to a comparable level of ground motion. The following generic electric power damage functions (based largely on medium voltage substations damage functions) are considered for lifeline interaction:

**Table 8.29: Generic Damage Algorithm for Electric Power System**

| Peak Ground Acceleration | | | |
|---|---|---|---|
| **Subcomponents** | **Damage State** | **Median (g)** | **β** |
| Loss of Commercial Power | slight/minor<br>moderate | 0.15<br>0.30 | 0.40<br>0.40 |

## 8.5.10 Guidance for Loss Estimation with Advanced Data and Models Analysis

For this type of analysis, the expert can use the methodology developed for User-Supplied Data Analysis with the flexibility to (1) include a refined inventory of the electric power system pertaining to the area of study, and (2) include component-specific and system-specific fragility data, and (3) perform a network analysis of actual circuits to better estimate the overall system functionality. Default damage algorithms for User-Supplied Data Analysis can be modified or replaced to accommodate any specified key component of an electric power system. Similarly, better restoration curves could be developed given knowledge of available resources and a more accurate layout of the network within the local topographic and geological conditions.

### 8.5.11 References

(1) ATC-13, "Earthquake Damage Evaluation Data for California", Applied Technology Council, Redwood City, CA, 1985.

(2) G&E Engineering Systems, Inc. (G&E), "NIBS Earthquake Loss Estimation Methods, Technical Manual, (Electric Power Systems)", June 1994.

(3) Schiff A., "Seismic Design Practices for Power Systems: Evolution, Evaluation, and Needs", TCLEE Monograph No. 4 August, 1991.

(4) Matsuda et al., "Earthquake Evaluation of a Substation Network", TCLEE Monograph No. 4 August, 1991.

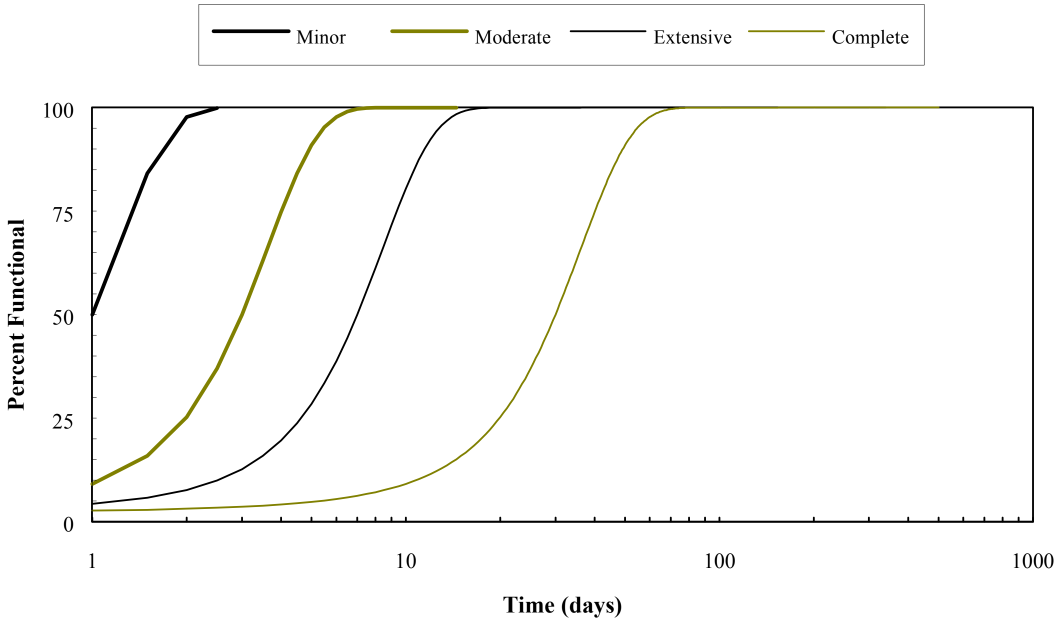


**Figure 8.43:  Restoration Curves for Electric Substations.**

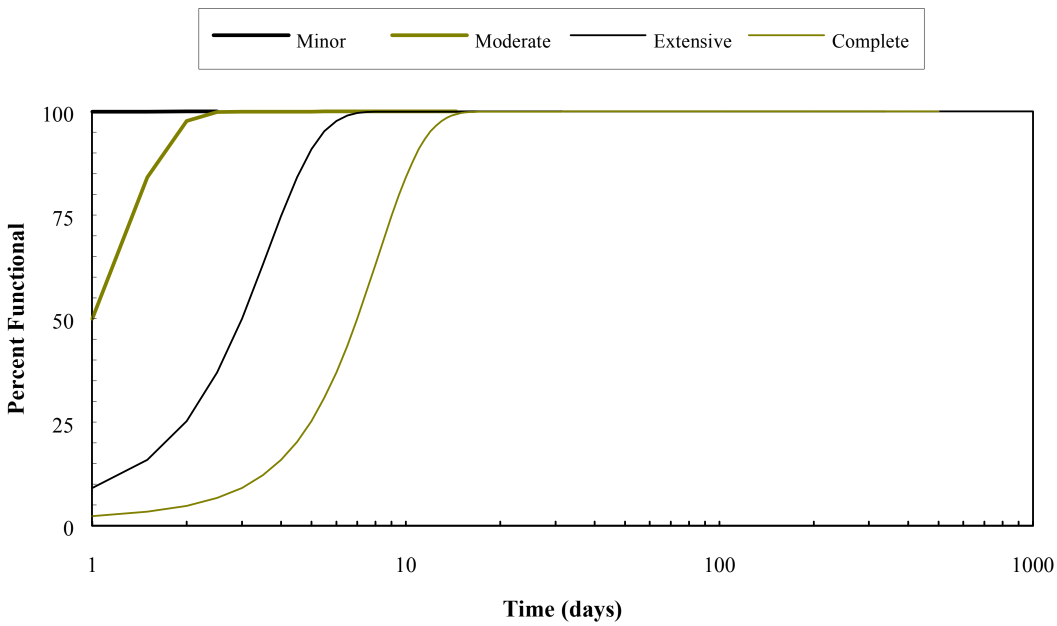


**Figure 8.44:  Restoration Curves for Distribution Circuits.**

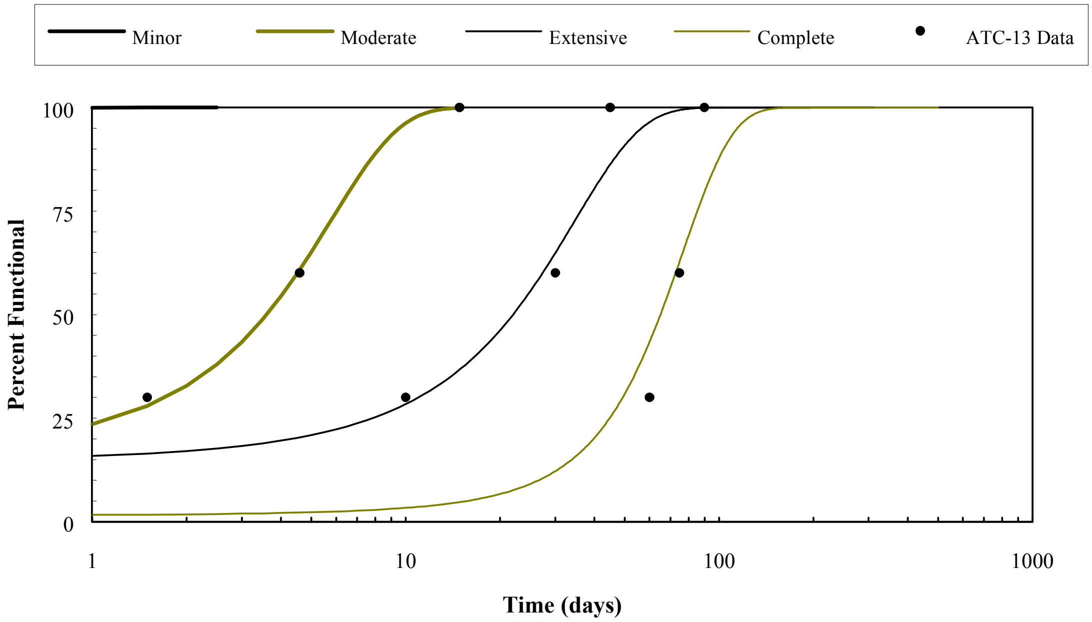


**Figure 8.45:  Restoration Curves for Generation Facilities.**

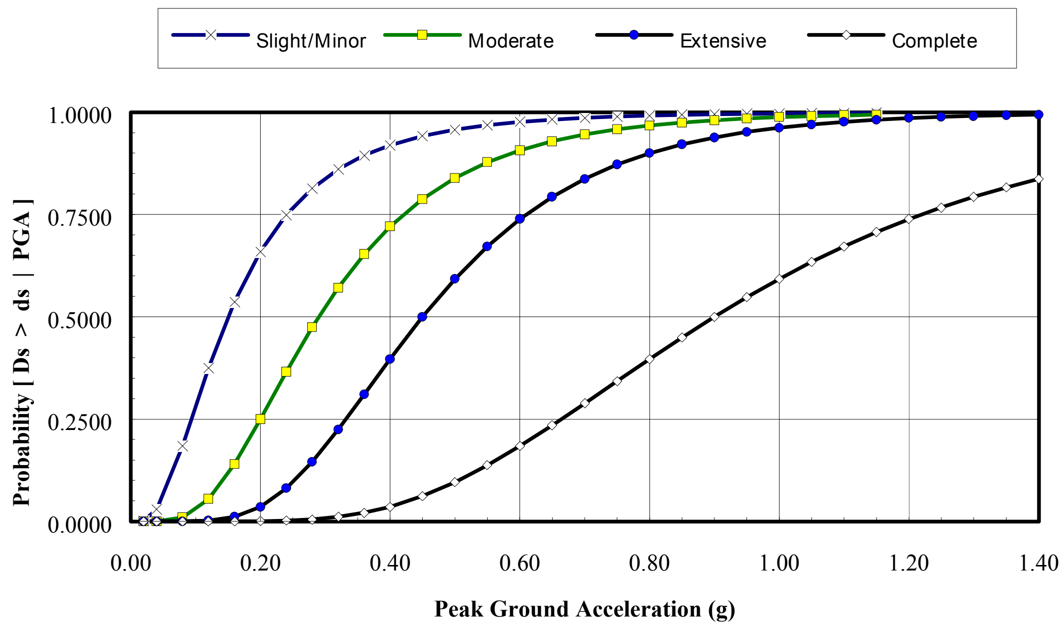


**Figure 8.46: Fragility Curves for Low voltage Substations with Seismic Components.**

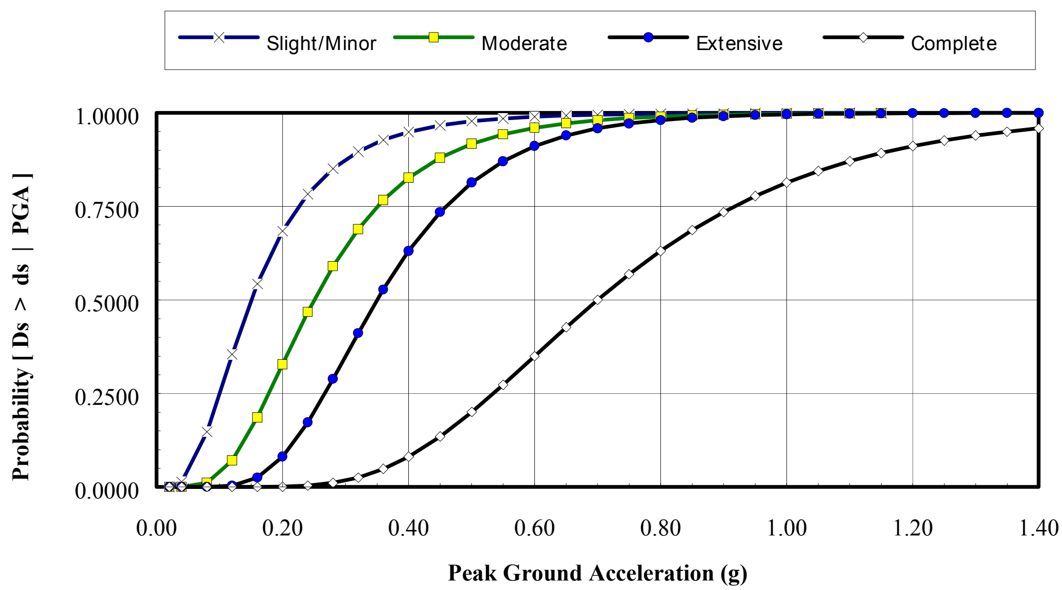


**Figure 8.47:  Fragility Curves for Medium Voltage Substations with Seismic Components.**

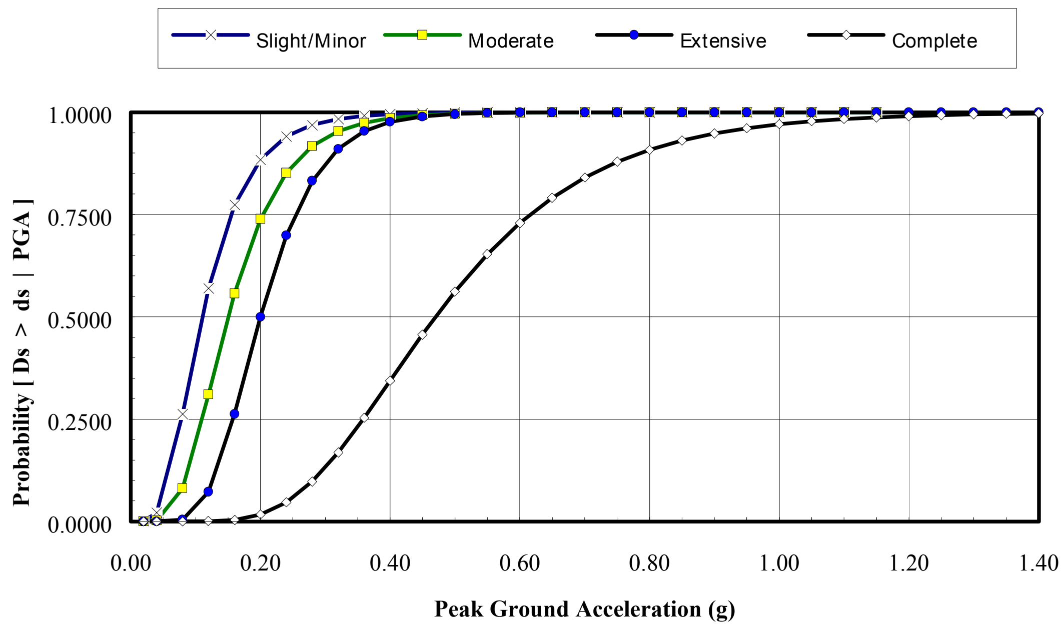


**Figure 8.48:  Fragility Curves for High Voltage Substations with Seismic Components.**

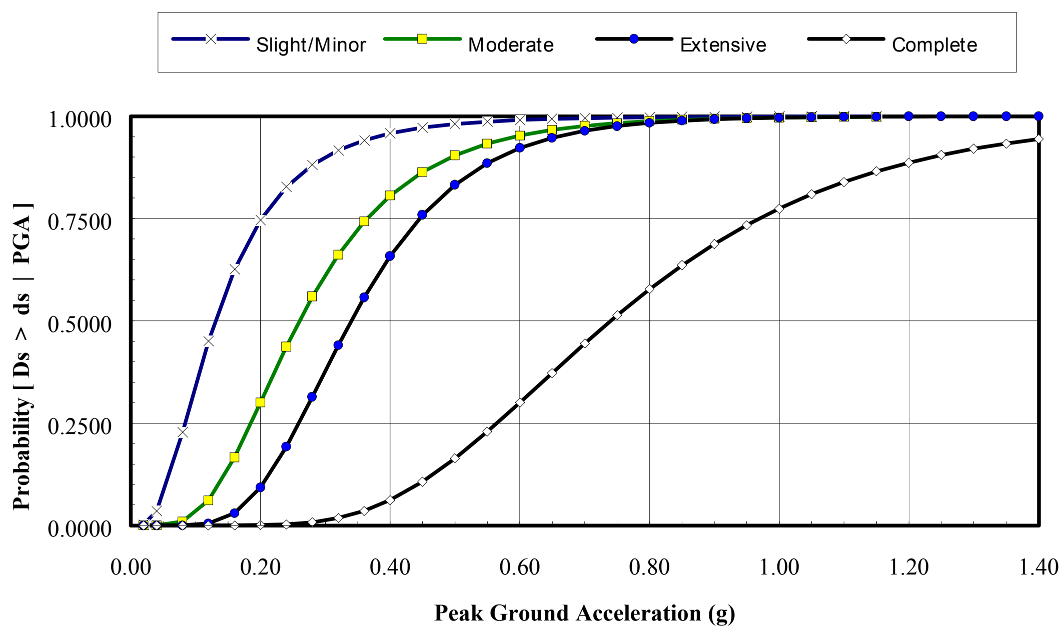


**Figure 8.49:  Fragility Curves for Low Voltage Substations with Standard Components.**

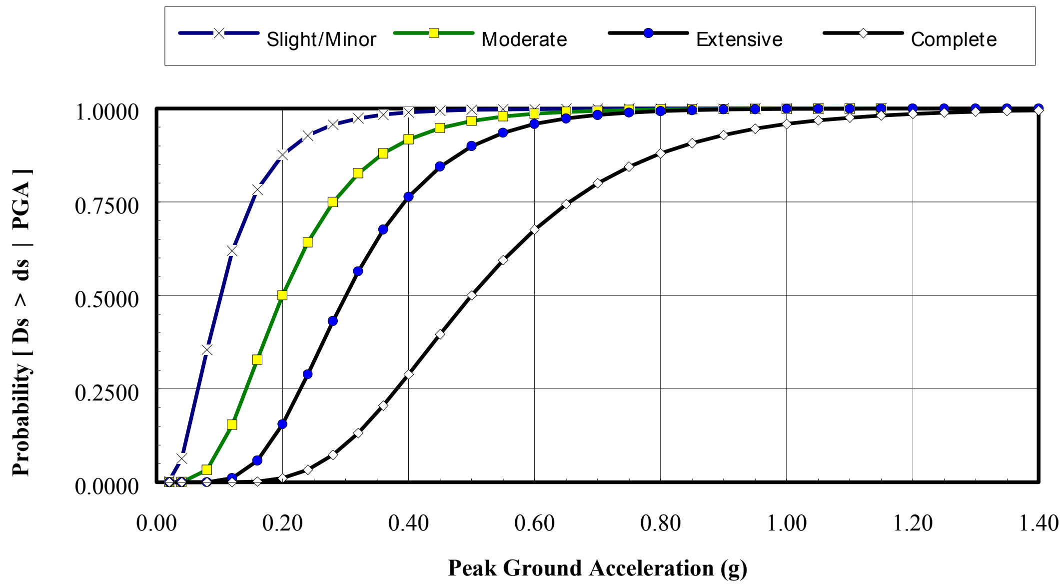


**Figure 8.50: Fragility Curves for Medium Voltage Substations with Standard Components.**

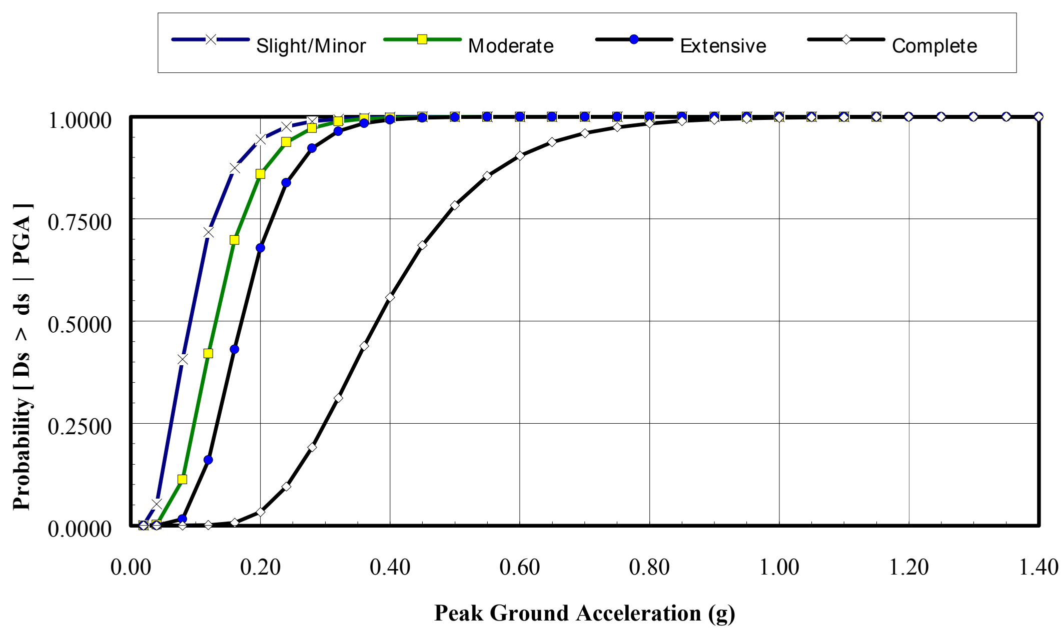


**Figure 8.51: Fragility Curves for High Voltage Substations with Standard Components.**

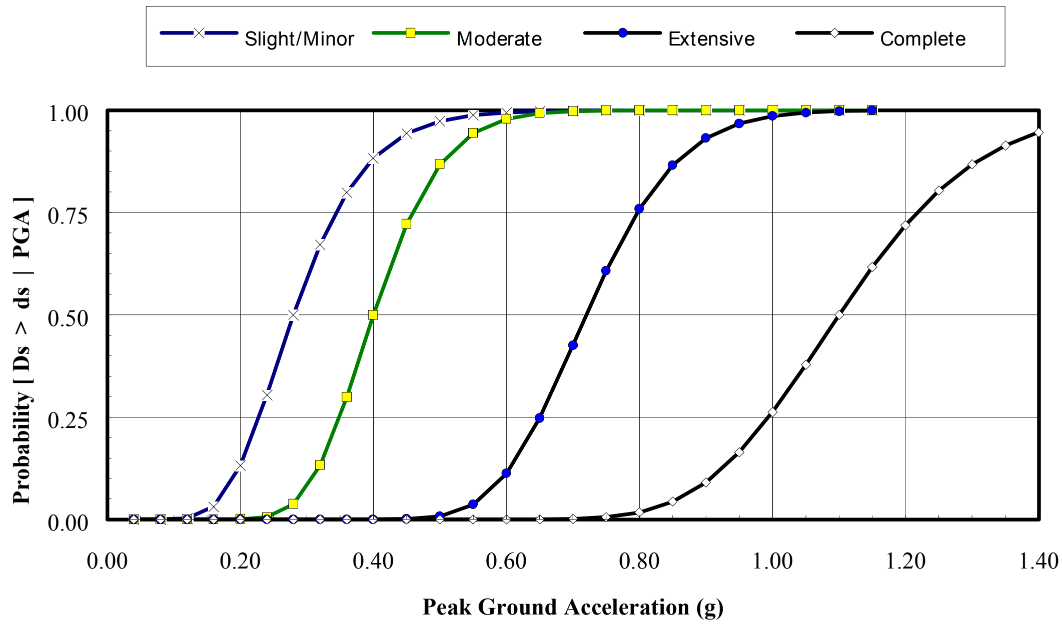


**Figure 8.52:  Fragility Curves for Seismic Distribution Circuits.**

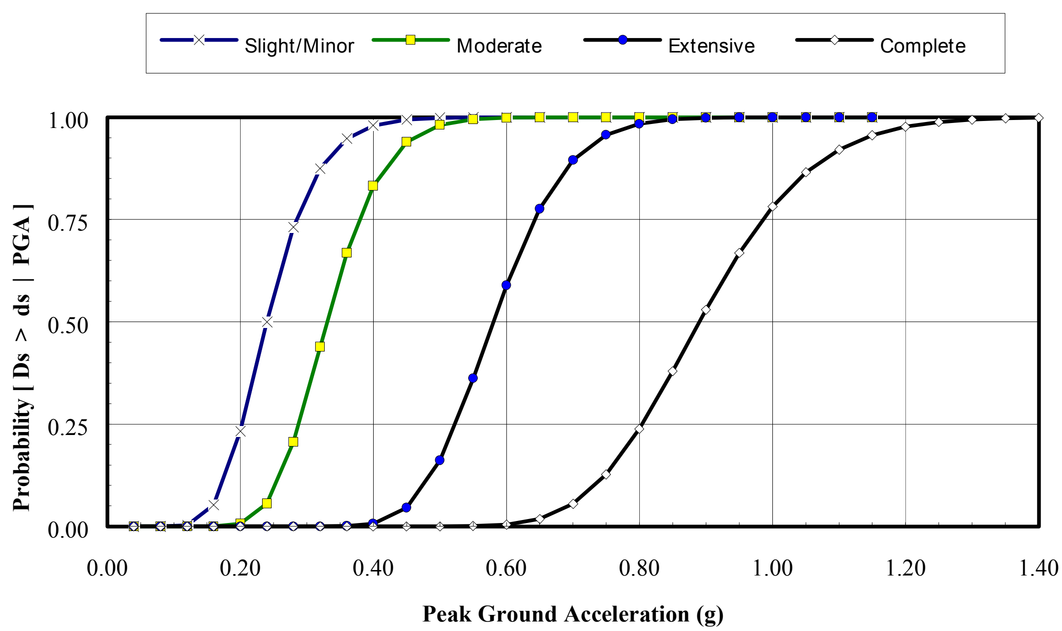


**Figure 8.53:  Fragility Curves for Standard Distribution Circuits.**

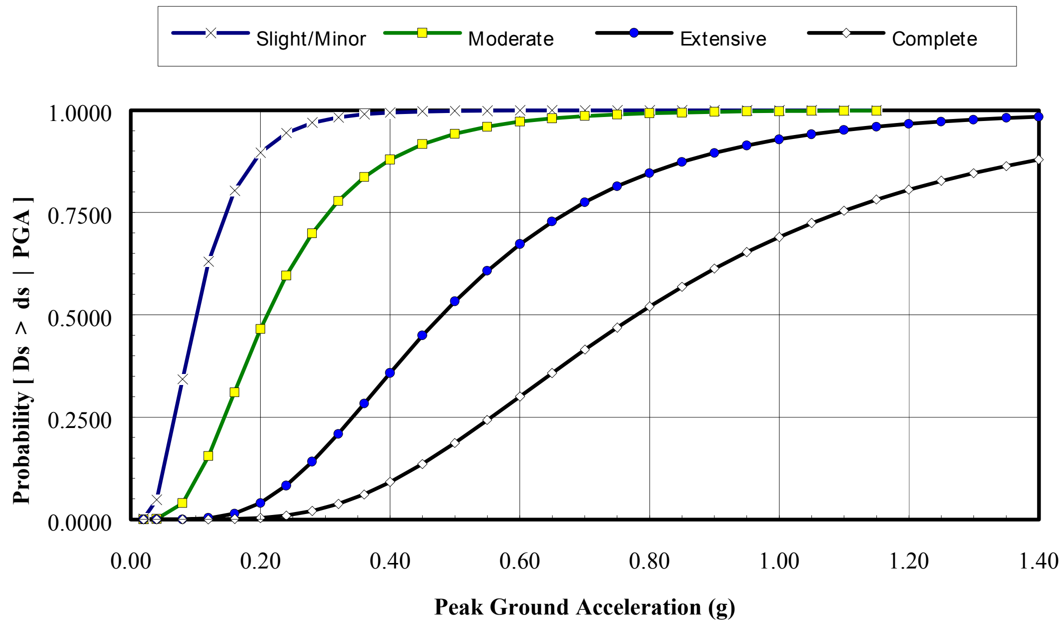


**Figure 8.54: Fragility Curves for Small Generation Facilities with Anchored Components.**

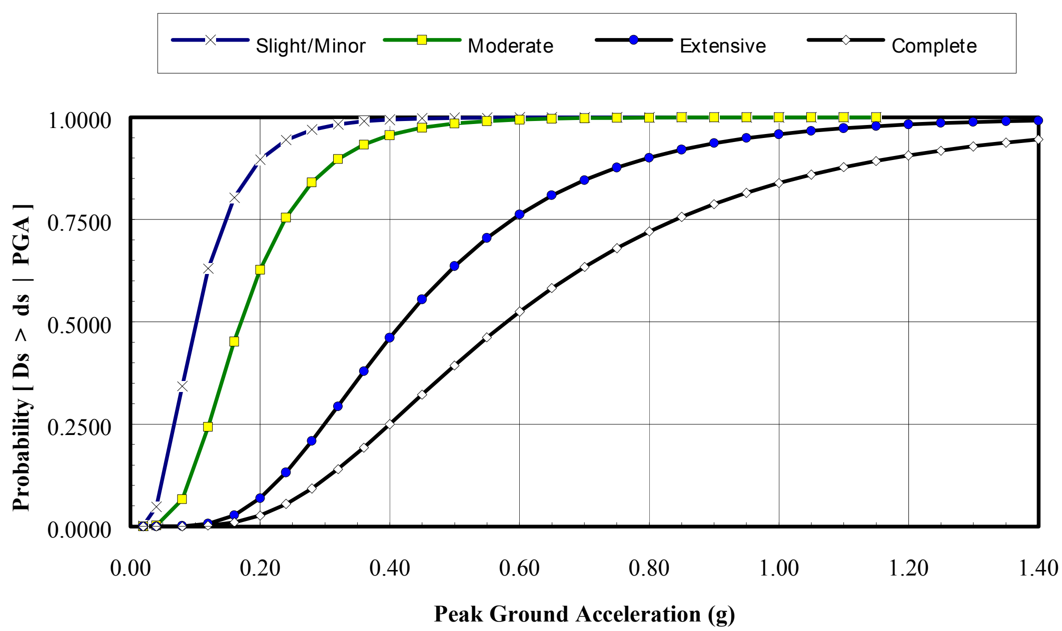


**Figure 8.55: Fragility Curves for Small Generation Facilities with Unanchored Components.**

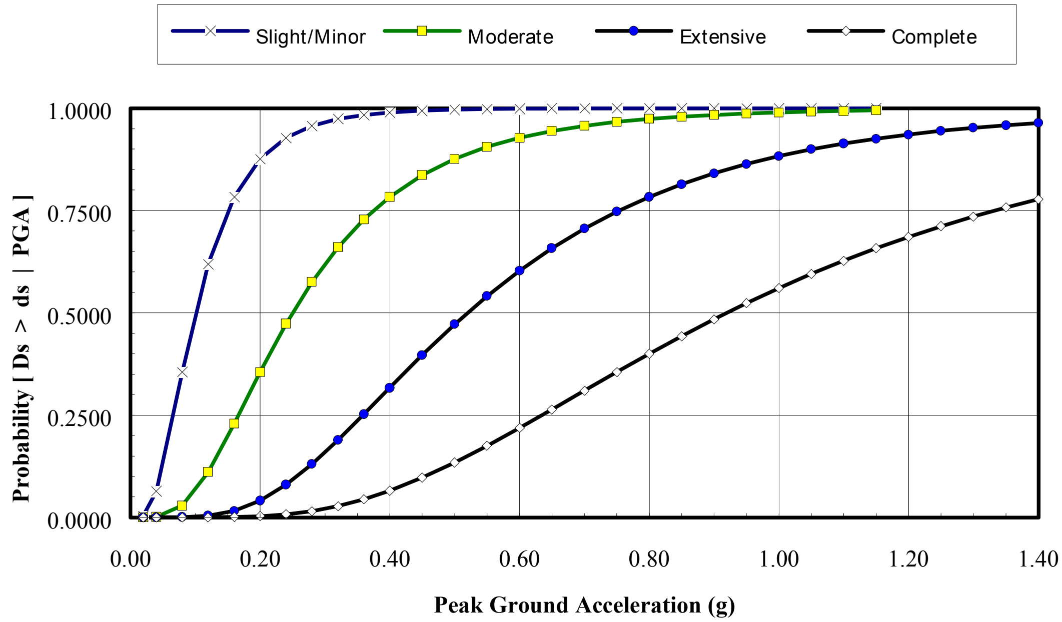


**Figure 8.56:  Fragility Curves for Medium/Large Generation Facilities with Anchored Components.**

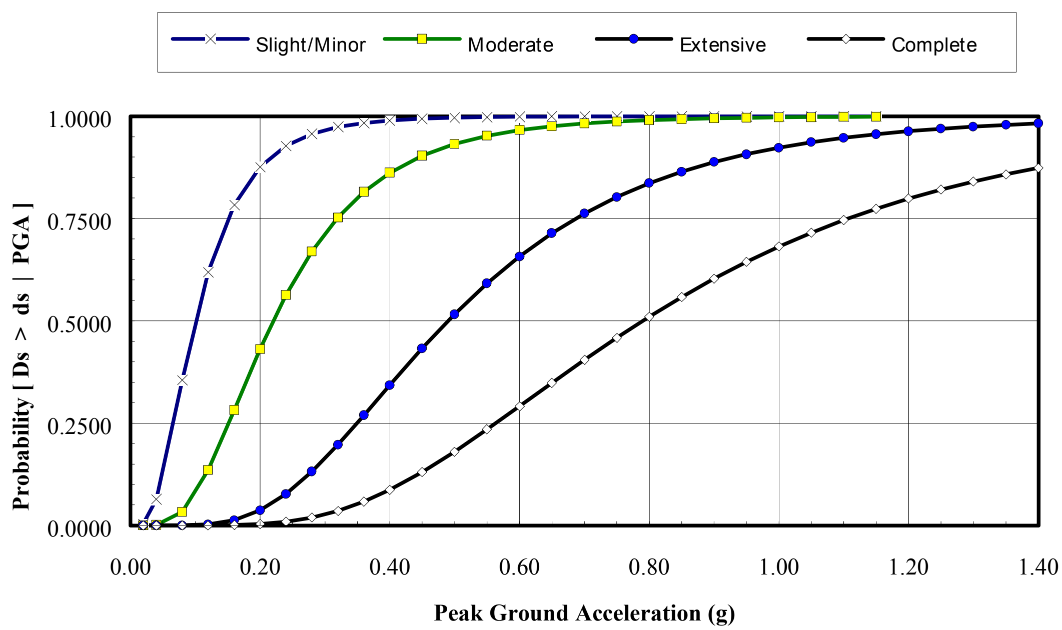


**Figure 8.57:  Fragility Curves for Medium/Large Generation Facilities with Unanchored Components.**

## 8.6 Communication Systems

### 8.6.1 Introduction

This section presents the loss estimation methodology for communication systems during earthquakes. The major components of a communication system are:

- Central offices and broadcasting stations (this includes all subcomponents such as central switching equipment)
- Transmission lines (these include all subcomponents such as equipment used to connect central office to end users)
- Cabling (low capacity links)

Central offices and broadcasting stations are the only components of the communication system considered in this section. Therefore, fragility curves are presented for these components only. Other components, such as cables and other lines, usually have enough slack to accomodate ground shaking and even moderate amounts of permanent ground deformations.

### 8.6.2 Scope

The scope of this section includes development of methods for estimation of earthquake damage to a communication facility given knowledge of its subcomponents (i.e., building type, switching equipment, backup power and off-site power), classification (i.e., for equipment, anchored versus unanchored components), and the ground motion (i.e., peak ground acceleration and/or permanent ground deformation).

Damage states describing the level of damage to a communication facility are defined (i.e. slight, moderate, extensive or complete). Fragility curves are developed for each classification of the communication system component. These curves describe the probability of reaching or exceeding each damage state given the level of ground motion or ground failure. Restoration curves are also provided to evaluate the loss of function.

### 8.6.3 Input Requirements and Output Information

Required input to estimate damage to a communication system includes the following items:

- Geographical location of the communication facility (longitude and latitude)
- PGA
- Classification

Direct damage output for a communication system includes probability estimates of (1) component (i.e. central office / broadcasting station) functionality and (2) damage, expressed in terms of the component's damage ratio. Damage ratios for a communication facility are presented in section 15.3 of Chapter 15.

### 8.6.4 Form of Damage Functions

Damage functions or fragility curves for communication facilities are modeled as lognormally-distributed functions that give the probability of reaching or exceeding different damage states for a given level of ground motion (quantified in terms of PGA) and ground failure (quantified in terms of PGD). Each of these fragility curves is characterized by a median value of ground motion and an associated dispersion factor (lognormal standard deviation). Definitions of various damage states and the methodology used in deriving all these fragility curves are presented in the following section.

### 8.6.5 Description of Communication System Components

As it was mentioned previously, only facilities are considered. A communication facility consists of a building (generic type is assumed in the methodology), central switching equipment (i.e., digital switches, anchored or unanchored), and back-up power supply (i.e. diesel generators or battery generators, anchored or unanchored) that may be needed to supply the requisite power to the center in case of loss of off-site power.

### 8.6.6 Definitions of Damage States

Communication facilities are susceptible to earthquake damage. A total of five damage states are defined for these components. These are none ($ds_1$), slight/minor ($ds_2$), moderate ($ds_3$), extensive ($ds_4$) and complete ($ds_5$).

**Slight/Minor Damage ($ds_2$)**

- Slight damage, $ds_2$ is defined by slight damage to the communication facility building, or inability of the center to provide services during a short period (few days) due to loss of electric power and backup power, if available.

**Moderate Damage ($ds_3$)**

- Moderate damage, $ds_3$ is defined by moderate damage to the communication facility building, few digital switching boards being dislodged, or the central office being out of service for a few days due to loss of electric power (i.e., power failure) and backup power (typically due to overload), if available.

**Extensive Damage ($ds_4$)**

- Extensive damage, $ds_4$ is defined by severe damage to the communication facility building resulting in limited access to facility, or by many digital switching boards being dislodged, resulting in malfunction.

**Complete Damage ($ds_5$)**

- Complete damage, $ds_5$ is defined by complete damage to the communication facility building, or damage beyond repair to digital switching boards.

### 8.6.7 Component Restoration Curves

Restoration functions are shown in Figures 8.58, 8.59 and 8.60. Figure 8.58 is based on ATC-13 social function SF-33a (first four damage states). The curves in this figure are obtained in a similar manner to the restoration curves for other lifeline systems. The parameters of these restoration curves are given in Table 8.30.a and 8.30.b. The best-fit normal distribution to the data shown in Figure 8.59 has a mean of 3 days and a standard deviation of 3 days. This restoration curve corresponds to the case where (1) the communication facility building does not suffer extensive damage (major structural damage would require extended period of time to repair), and (2) the communication network did not suffer extensive damage. In essence, the plotted restoration curve in Figure 8.59 corresponds to the communication facility being in moderate to extensive damage state, according to the definitions of damage states presented herein.

**Table 8.30.a: Continuous Restoration Functions for Communication Facilities (After ATC-13, 1985)**

| Restoration Functions (All Normal Distributions) | | | |
|---|---|---|---|
| **Classification** | **Damage State** | **Mean (Days)** | **σ** |
| Communication facility | slight/minor | 0.5 | 0.2 |
| | moderate | 1 | 1.0 |
| | extensive | 7 | 7.0 |
| | complete | 40 | 40.0 |

**Table 8.30.b: Discretized Restoration Functions for Communication Facilities**

| Discretized Restoration Functions | | | | | | |
|---|---|---|---|---|---|---|
| **Classification** | **Damage State** | **1 day** | **3 days** | **7 days** | **30 days** | **90 days** |
| Communication facility | slight/minor | 99 | 100 | 100 | 100 | 100 |
| | moderate | 50 | 98 | 100 | 100 | 100 |
| | extensive | 20 | 28 | 50 | 100 | 100 |
| | complete | 16 | 18 | 20 | 40 | 89 |

A recently published paper by Tang and Wong (1994) on the performance of telecommunication systems in the Northridge Earthquake of January 17, 1994 indicates that within three days the system stabilized. Table 8.31 shows the system performance during the three days following that quake.

**Table 8.31: Daily Call Attempts as Recorded in a Central Office in the Afflicted Area (Tang and Wong, 1994)**

| | Daily Call Attempts in 1,000s | | | | |
|---|---|---|---|---|---|
| | **Jan 17** | **Jan 18** | **Jan 19** | **Jan 20** | **1993 Average** |
| **Call Attemtps** | 5,455 | 4,237 | 3,240 | 2,860 | 1,500 |
| **Performance** | 86.9% | 95.2% | 96.0% | 97.6% | 99.3% |

### 8.6.8 Development of Damage Functions

In this subsection, damage functions for the central offices are presented. Fragility curves for these components are based on the probabilistic combination of subcomponent damage functions using Boolean expressions to describe the relationship of subcomponents to the component. It should be mentioned that the Boolean logic is implicitly presented within the definition of the damage state (see section 8.1.8 for an example). Note also that damage functions due to ground failure (i.e., PGD) for central offices are assumed to be similar to those described for potable water system facilities.

PGA related damage functions are given in terms of median values and dispersions for each damage state in Table 8.32. These are also plotted in Figures 8.61.a and 8.61.b.

**Table 8.32: Damage Algorithms for Communication Facilities**

| Peak Ground Acceleration | | | |
|---|---|---|---|
| **Classification** | **Damage State** | **Median (g)** | **β** |
| Facilities with anchored components | slight/minor | 0.15 | 0.75 |
| | moderate | 0.32 | 0.60 |
| | extensive | 0.60 | 0.62 |
| | complete | 1.25 | 0.65 |
| Facilities with unanchored components | slight/minor | 0.13 | 0.55 |
| | moderate | 0.26 | 0.50 |
| | extensive | 0.46 | 0.62 |
| | complete | 1.03 | 0.62 |

### 8.6.9 Guidance for Loss Estimation Using Advanced Data and Models Analysis

For this type of analysis, the expert can use the methodology developed for the User-Supplied Data Analysis with the flexibility to: (1) include a refined inventory of the communication system pertaining to the area of study, and (2) include specific and system specific fragility data. Default damage algorithms for User-Supplied Data Analysis, can be modified or replaced to accommodate any specified key component of a communication system, such as switching equipment. Similarly, better restoration curves could be developed given knowledge of the redundancy importance of a communication system components in the network, the availability of resources and a more accurate layout of the communication network within the local topographic and geological conditions.

### 8.6.10 References

(1) Tang A. and Wong F., "Observation on Telecommunications Lifeline Performance in the Northridge Earthquake of January 17, 1994, Magnitude 6.6", 1994.

(2) Tang A., "Two Decades of Communications Systems Seismic Protection Improvements", TCLEE Monograph No. 4 August, 1991.

(3) G&E Engineering Systems, Inc. (G&E), "NIBS Earthquake Loss Estimation Methods, Technical Manual, (Communication Systems)", June 1994.

(4) ATC-13, "Earthquake Damage Evaluation Data for California", Applied Technology Council, Redwood City, CA, 1985.

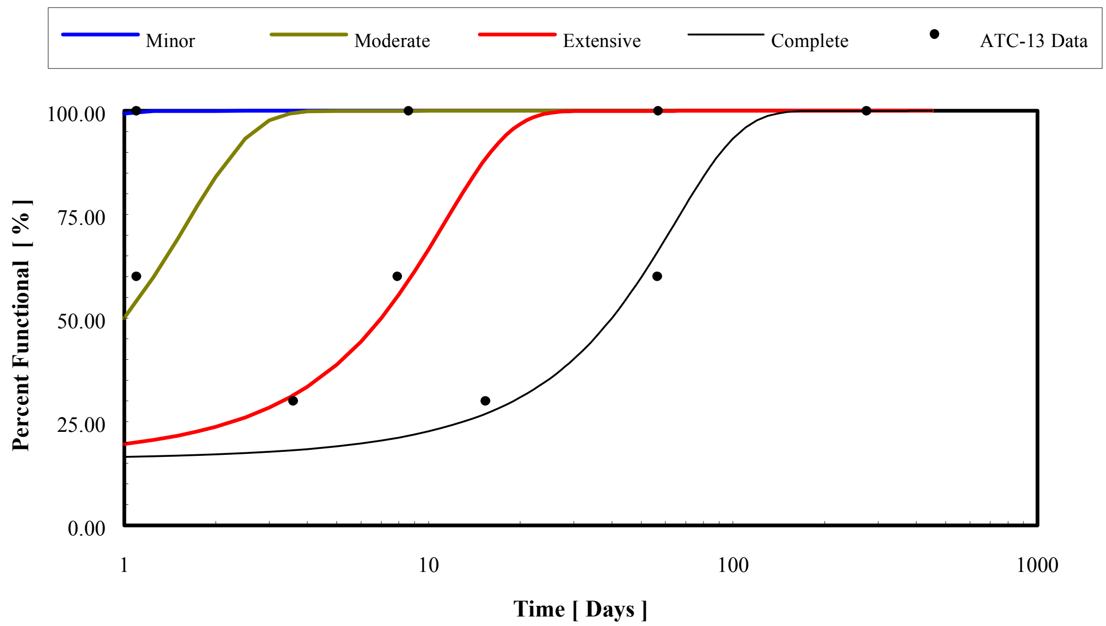


**Figure 8.58: Restoration Curves for Central Offices (after ATC-13, 1985).**

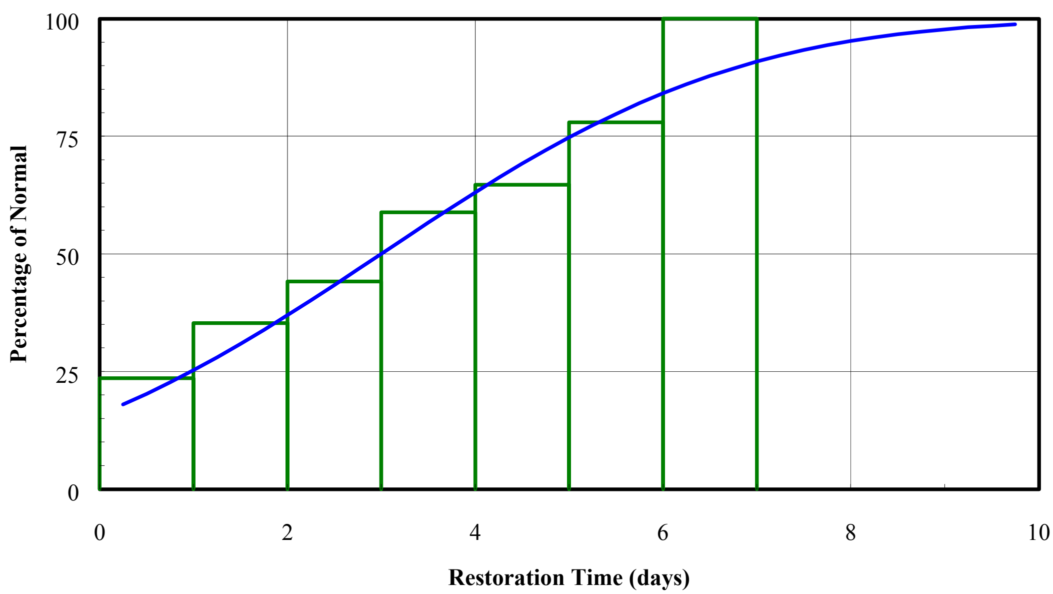


**Figure 8.59: Restoration Curve for Communication System Service: Normal Service (After G&E, 1994).**

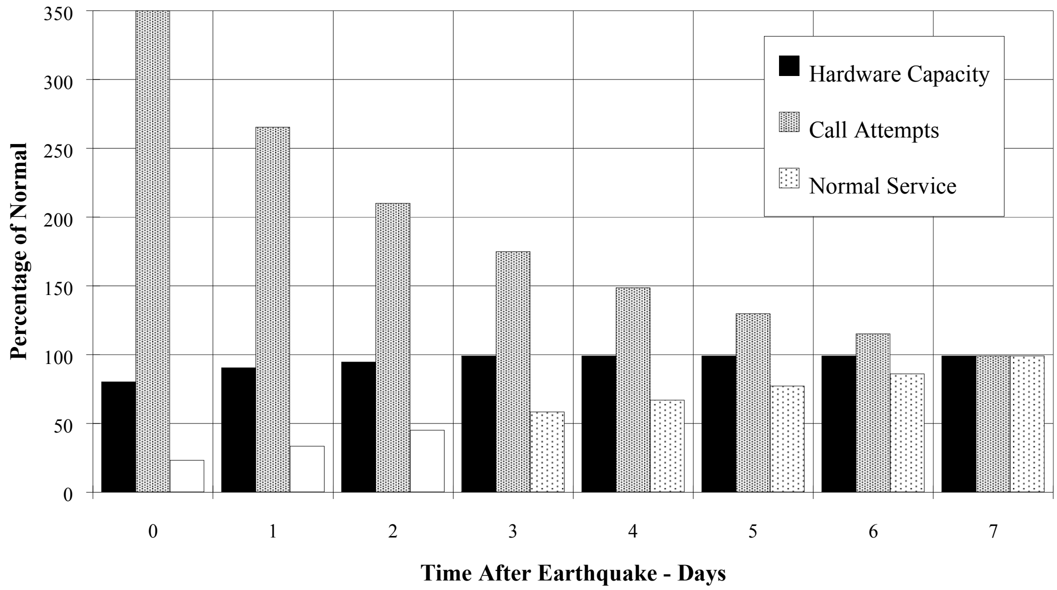


**Figure 8.60:  Communication System Service Restoration (after G&E, 1994).**

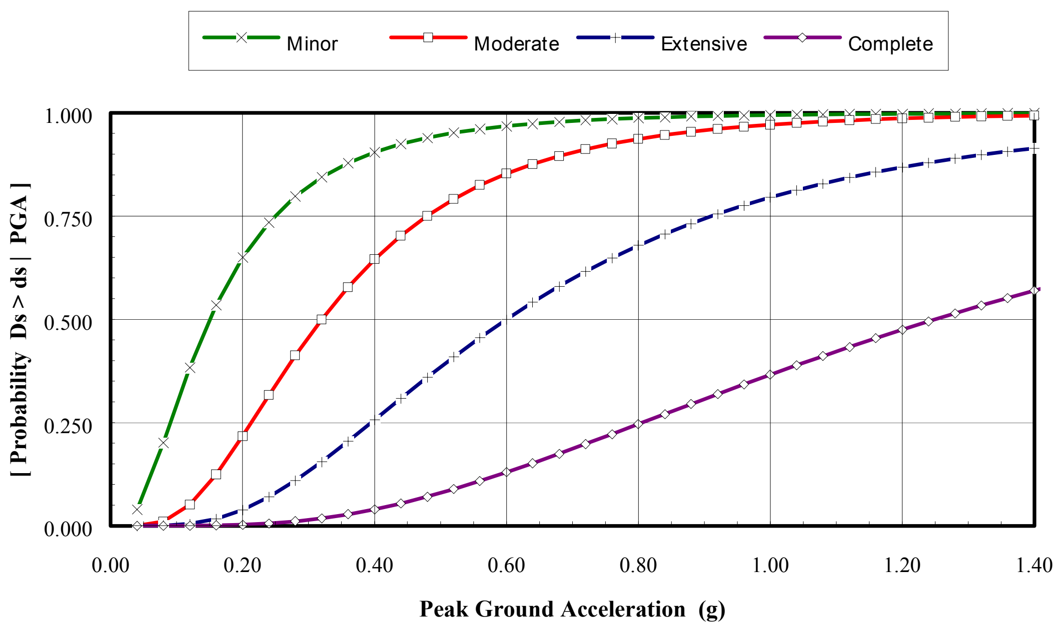


**Figure 8.61.a:  Fragility Curves for Communication Systems with Anchored Components.**

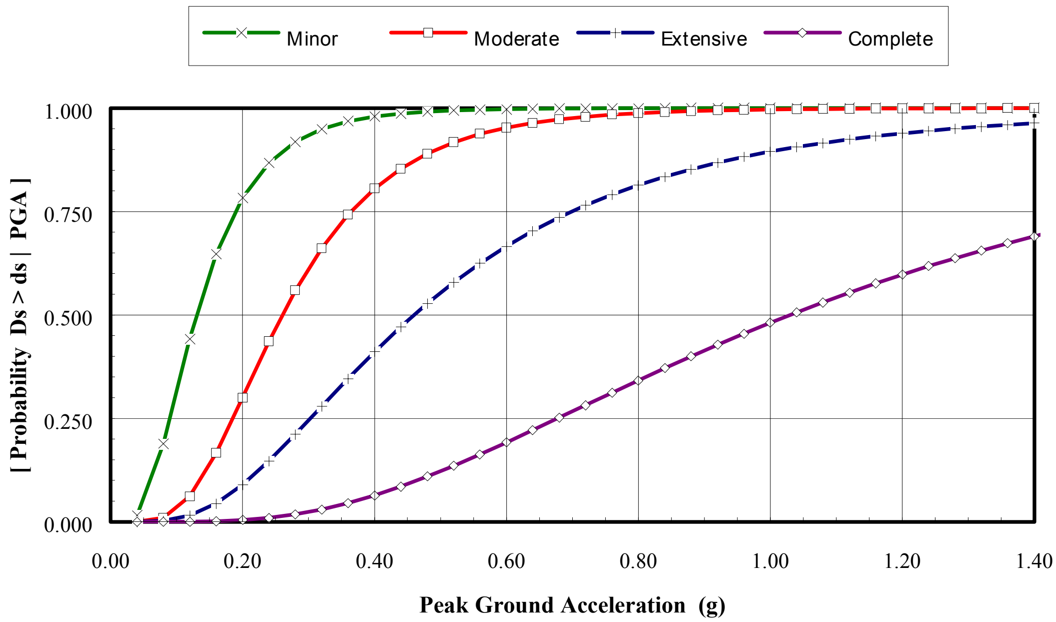


**Figure 8.61.b: Fragility Curves for Communication Systems with Unanchored Components.**

# Appendix 8A
# Subcomponent Damage Functions for Potable Water Systems

Any given subcomponent in the lifeline methodology can experience all five damage states; however, the only damage states listed in the appendices of Chapters 7 and 8 are the ones used in the fault tree logic of the damage state of interest of the component.

**Table A.8.1: Subcomponent Damage Algorithms for Pumping Plants With Anchored Components (after G&E, 1994)**

| Peak Ground Acceleration | | | |
|---|---|---|---|
| **Subcomponents** | **Damage State** | **Median (g)** | **β** |
| Electric Power (Backup) | minor<br>moderate | 0.80<br>1.00 | 0.60<br>0.80 |
| Loss of commercial Power | minor<br>moderate | 0.15<br>0.30 | 0.40<br>0.40 |
| Vertical/ Horizontal Pump* | extensive | 1.25/1.60 | 0.60 |
| Building | minor<br>moderate<br>extensive<br>complete | 0.15<br>0.40<br>0.80<br>1.50 | 0.80<br>0.80<br>0.80<br>0.80 |
| Equipment | moderate | 1.00 | 0.60 |

* Difference in median values has little effect on the fault tree analysis

**Table A.8.2: Subcomponent Damage Algorithms for Pumping Plants with Unanchored Components (after G&E, 1994)**

| Peak Ground Acceleration | | | |
|---|---|---|---|
| **Subcomponents** | **Damage State** | **Median (g)** | **β** |
| Electric Power (Backup) | minor<br>moderate | 0.20<br>0.40 | 0.60<br>0.80 |
| Loss of commercial Power | minor<br>moderate | 0.15<br>0.30 | 0.40<br>0.40 |
| Vertical/ Horizontal Pump* | extensive | 1.25/1.60 | 0.60 |
| Building | minor<br>moderate<br>extensive<br>complete | 0.15<br>0.40<br>0.80<br>1.50 | 0.80<br>0.80<br>0.80<br>0.80 |
| Equipment | moderate | 0.60 | 0.60 |

* Difference in median values has little effect on the fault tree analysis

**Table A.8.3: Subcomponent Damage Algorithms for Wells with Anchored Components (after G&E 1994)**

| Peak Ground Acceleration | | | |
|---|---|---|---|
| **Subcomponents** | **Damage State** | **Median (g)** | **β** |
| Electric Power (Backup) | minor<br>moderate | 0.80<br>1.00 | 0.60<br>0.80 |
| Loss of commercial Power | minor<br>moderate | 0.15<br>0.30 | 0.40<br>0.40 |
| Well Pump | extensive | 1.00 | 0.60 |
| Building | minor<br>moderate<br>extensive<br>complete | 0.15<br>0.40<br>0.80<br>1.50 | 0.80<br>0.80<br>0.80<br>0.80 |
| Electric Equipment | moderate | 1.00 | 0.60 |

**Table A.8.4: Subcomponent Damage Algorithms for Wells with Unanchored Components (after G&E 1994)**

| Peak Ground Acceleration | | | |
|---|---|---|---|
| **Subcomponents** | **Damage State** | **Median (g)** | **β** |
| Electric Power (Backup) | minor<br>moderate | 0.20<br>0.40 | 0.60<br>0.80 |
| Loss of commercial Power | minor<br>moderate | 0.15<br>0.30 | 0.40<br>0.40 |
| Well Pump | extensive | 1.00 | 0.60 |
| Building | minor<br>moderate<br>extensive<br>complete | 0.15<br>0.40<br>0.80<br>1.50 | 0.80<br>0.80<br>0.80<br>0.80 |
| Electric Equipment | moderate | 0.60 | 0.60 |

**Table A.8.5: Subcomponent Damage Algorithms for Sedimentation/Flocculation System (after G&E 1994)**

| Peak Ground Acceleration | | | |
|---|---|---|---|
| **Subcomponents** | **Damage State** | **Median (g)** | **β** |
| Basins | minor | 0.40 | 0.60 |
| Baffles | minor | 0.70 | 0.60 |
| Paddles | moderate | 0.80 | 0.60 |
| Scrapers | moderate | 0.90 | 0.60 |

**Table A.8.6: Subcomponent Damage Algorithms for Water Treatment Plants with Anchored Components (after G&E 1994)**

| Peak Ground Acceleration | | | |
|---|---|---|---|
| **Subcomponents** | **Damage State** | **Median (g)** | **β** |
| Electric Power (Backup) | minor<br>moderate | 0.80<br>1.00 | 0.60<br>0.80 |
| Loss of commercial Power | minor<br>moderate | 0.15<br>0.30 | 0.40<br>0.40 |
| Chlorination Equipment | minor<br>moderate | 0.65<br>1.00 | 0.60<br>0.70 |
| Sediment Flocculation | minor<br>moderate | 0.36<br>0.60 | 0.50<br>0.50 |
| Chemical Tanks | minor<br>moderate | 0.40<br>0.65 | 0.70<br>0.70 |
| Electric Equipment | moderate | 1.00 | 0.60 |
| Elevated Pipe | extensive<br>complete | 0.53<br>1.00 | 0.60<br>0.60 |
| Filter Gallery | complete | 2.00 | 1.00 |

**Table A.8.7: Subcomponent Damage Algorithms for Water Treatment Plants with Unanchored Components (after G&E 1994)**

| Peak Ground Acceleration | | | |
|---|---|---|---|
| **Subcomponents** | **Damage State** | **Median (g)** | **β** |
| Electric Power (Backup) | minor<br>moderate | 0.20<br>0.40 | 0.60<br>0.80 |
| Loss of commercial Power | minor<br>moderate | 0.15<br>0.30 | 0.40<br>0.40 |
| Chlorination Equipment | minor<br>moderate | 0.35<br>0.70 | 0.60<br>0.70 |
| Sediment Flocculation | minor<br>moderate | 0.36<br>0.60 | 0.50<br>0.50 |
| Chemical Tanks | minor<br>moderate | 0.25<br>0.40 | 0.60<br>0.60 |
| Electric Equipment | moderate | 0.60 | 0.60 |
| Elevated Pipe | extensive<br>complete | 0.53<br>1.00 | 0.60<br>0.60 |
| Filter Gallery | complete | 2.00 | 1.00 |

# APPENDIX 8B
# Subcomponent Damage Functions for Waste Water Systems

**Table B.8.1: Subcomponent Damage Algorithms for Waste Water Treatment Plants with Anchored Components (after G&E, 1994)**

| Peak Ground Acceleration | | | |
|---|---|---|---|
| **Subcomponents** | **Damage State** | **Median (g)** | **β** |
| Electric Power (Backup) | minor<br>moderate | 0.80<br>1.00 | 0.60<br>0.80 |
| Loss of commercial Power | minor<br>moderate | 0.15<br>0.30 | 0.40<br>0.40 |
| Chlorination Equipment | minor<br>moderate | 0.65<br>1.00 | 0.60<br>0.70 |
| Sediment Flocculation | minor<br>moderate<br>extensive | 0.36<br>0.60<br>1.20 | 0.50<br>0.50<br>0.60 |
| Chemical Tanks | minor<br>moderate | 0.40<br>0.65 | 0.70<br>0.70 |
| Electrical/ Mechanical Equipment | moderate | 1.00 | 0.60 |
| Elevated Pipe | extensive<br>complete | 0.53<br>1.00 | 0.60<br>0.60 |
| Buildings | complete | 1.50 | 0.80 |

**Table B.8.2: Subcomponent Damage Algorithms for Waste Water Treatment Plants with Unanchored Components (after G&E, 1994)**

| Peak Ground Acceleration | | | |
|---|---|---|---|
| **Subcomponents** | **Damage State** | **Median (g)** | **β** |
| Electric Power (Backup) | minor<br>moderate | 0.20<br>0.40 | 0.60<br>0.80 |
| Loss of com-mercial Power | minor<br>moderate | 0.15<br>0.30 | 0.40<br>0.40 |
| Chlorination Equipment | minor<br>moderate | 0.35<br>0.70 | 0.60<br>0.70 |
| Sediment Flocculation | minor<br>moderate<br>extensive | 0.36<br>0.60<br>1.20 | 0.50<br>0.50<br>0.60 |
| Chemical Tanks | minor<br>moderate | 0.25<br>0.40 | 0.60<br>0.60 |
| Electrical/ Mechanical Equipment | moderate | 0.60 | 0.60 |
| Elevated Pipe | extensive<br>complete | 0.53<br>1.00 | 0.60<br>0.60 |
| Buildings | complete | 1.50 | 0.80 |

# APPENDIX 8C
# Subcomponent Damage Functions for Oil Systems

**Table C.8.1: Subcomponent Damage Algorithms for Refineries with Anchored Components (after G&E, 1994)**

| Peak Ground Acceleration | | | |
|---|---|---|---|
| **Subcomponents** | **Damage State** | **Median (g)** | **β** |
| ElectricPower (Backup) | minor<br>moderate | 0.80<br>1.00 | 0.60<br>0.80 |
| Loss of com-mercial Power | minor<br>moderate | 0.15<br>0.30 | 0.40<br>0.40 |
| Electrical/ Mechanical Equipment | moderate | 1.00 | 0.60 |
| Tanks | minor<br>moderate<br>extensive<br>complete | 0.30<br>0.70<br>1.25<br>1.60 | 0.60<br>0.60<br>0.65<br>0.60 |
| Stacks | extensive | 0.75 | 0.70 |
| Elevated Pipe | complete | 1.00 | 0.60 |

**Table C.8.2: Subcomponent Damage Algorithms for Refineries with Unanchored Components (after G&E, 1994)**

| Peak Ground Acceleration | | | |
|---|---|---|---|
| **Subcomponents** | **Damage State** | **Median (g)** | **β** |
| Electric Power (Backup) | minor<br>moderate | 0.20<br>0.40 | 0.60<br>0.80 |
| Loss of com-mercial Power | minor<br>moderate | 0.15<br>0.30 | 0.40<br>0.40 |
| Electrical/ Mechanical Equipment | moderate | 0.60 | 0.60 |
| Tanks | minor<br>moderate<br>extensive<br>complete | 0.15<br>0.35<br>0.68<br>0.95 | 0.70<br>0.75<br>0.75<br>0.70 |
| Stacks | extensive | 0.60 | 0.70 |
| Elevated Pipe | complete | 1.00 | 0.60 |

**Table C.8.3: Subcomponent Damage Algorithms for Pumping Plants with Anchored Components (after G&E, 1994)**

| Peak Ground Acceleration | | | |
|---|---|---|---|
| **Subcomponents** | **Damage State** | **Median (g)** | **β** |
| Electric Power (Backup) | minor<br>moderate | 0.80<br>1.00 | 0.60<br>0.80 |
| Loss of commercial Power | minor<br>moderate | 0.15<br>0.30 | 0.40<br>0.40 |
| Vertical/ Horiz. Pump* | extensive | 1.25/1.60 | 0.60 |
| Building | minor<br>moderate<br>extensive<br>complete | 0.15<br>0.40<br>0.80<br>1.50 | 0.80<br>0.80<br>0.80<br>0.80 |
| Electrical/ Mechanical Equipment | moderate | 1.00 | 0.60 |

* Difference in median values has little effect on the fault tree analysis

**Table C.8.4: Subcomponent Damage Algorithms for Pumping Plants with Unanchored Components (after G&E, 1994)**

| Peak Ground Acceleration | | | |
|---|---|---|---|
| **Subcomponents** | **Damage State** | **Median (g)** | **β** |
| Electric Power (Backup) | minor<br>moderate | 0.20<br>0.40 | 0.60<br>0.80 |
| Loss of commercial Power | minor<br>moderate | 0.15<br>0.30 | 0.40<br>0.40 |
| Vertical/ Horizontal Pump* | extensive | 1.25/1.60 | 0.60 |
| Building | minor<br>moderate<br>extensive<br>complete | 0.15<br>0.40<br>0.80<br>1.50 | 0.80<br>0.80<br>0.80<br>0.80 |
| Electrical/ Mechanical Equipment | moderate | 0.60 | 0.60 |

- Difference in median values has little effect on the fault tree analysis

**Table C.8.5: Subcomponent Damage Algorithms for Tank Farms with Anchored Components (after G&E, 1994)**

| Peak Ground Acceleration | | | |
|---|---|---|---|
| **Subcomponents** | **Damage State** | **Median (g)** | **β** |
| ElectricPower (Backup) | minor<br>moderate | 0.80<br>1.00 | 0.60<br>0.80 |
| Loss of commercial Power | minor<br>moderate | 0.15<br>0.30 | 0.40<br>0.40 |
| Electrical/ Mechanical Equipment | moderate | 1.00 | 0.60 |
| Tanks | minor<br>moderate<br>extensive<br>complete | 0.30<br>0.70<br>1.25<br>1.60 | 0.60<br>0.60<br>0.65<br>0.60 |
| Elevated Pipes | extensive<br>complete | 0.53<br>1.00 | 0.60<br>0.60 |

**Table C.8.6: Subcomponent Damage Algorithms for Tank Farms with Unanchored Components (after G&E, 1994)**

| Peak Ground Acceleration | | | |
|---|---|---|---|
| **Subcomponents** | **Damage State** | **Median (g)** | **β** |
| ElectricPower (Backup) | minor<br>moderate | 0.20<br>0.40 | 0.60<br>0.80 |
| Loss of Commercial Power | minor<br>moderate | 0.15<br>0.30 | 0.40<br>0.40 |
| Electrical/ Mechanical Equipment | moderate | 0.60 | 0.60 |
| Tanks | minor<br>moderate<br>extensive<br>complete | 0.15<br>0.35<br>0.68<br>0.95 | 0.70<br>0.75<br>0.75<br>0.70 |
| Elevated Pipes | extensive<br>complete | 0.53<br>1.00 | 0.60<br>0.60 |

# APPENDIX 8D
# Subcomponent Damage Functions for Electric Power Systems

**Table D.8.1: Damage Algorithms for Subcomponents of Low Voltage Substations with Anchored Subcomponents (after G&E, 1994)**

| Peak Ground Acceleration | | | |
|---|---|---|---|
| **Classification** | **Damage State** | **Median (g)** | **β** |
| Transformer | All* | 0.75 | 0.70 |
| Disconnect Switches | All* | 1.20 | 0.70 |
| Live Tank Circuit Breaker | All* | 1.0 | 0.70 |
| Current Transformer | All* | 0.75 | 0.70 |

* Damage state depends on the percentage of the subcomponents failing

**Table D.8.2: Damage Algorithms for Subcomponents of Low Voltage Substations with Unanchored Subcomponents (after G&E, 1994)**

| Peak Ground Acceleration | | | |
|---|---|---|---|
| **Classification** | **Damage State** | **Median (g)** | **β** |
| Transformer | All* | 0.50 | 0.70 |
| Disconnect Switches | All* | 0.90 | 0.70 |
| Live Tank Circuit Breaker | All* | 0.60 | 0.70 |
| Current Transformer | All* | 0.75 | 0.70 |

* Damage state depends on the percentage of the subcomponents failing

**Table D.8.3: Damage Algorithms for Subcomponents of Medium Voltage Substations with Anchored Subcomponents (after G&E, 1994)**

| Peak Ground Acceleration | | | |
|---|---|---|---|
| **Classification** | **Damage State** | **Median (g)** | **β** |
| Transformer | All* | 0.60 | 0.70 |
| Disconnect Switches | All* | 0.75 | 0.70 |
| Live Tank Circuit Breaker | All* | 0.70 | 0.70 |
| Current Transformer | All* | 0.50 | 0.70 |

* Damage state depends on the percentage of the subcomponents failing

**Table D.8.4: Damage Algorithms for Subcomponents of Medium Voltage Substations with Unnchored Subcomponents (after G&E, 1994)**

| Peak Ground Acceleration | | | |
|---|---|---|---|
| **Classification** | **Damage State** | **Median (g)** | **β** |
| Transformer | All* | 0.30 | 0.70 |
| Disconnect Switches | All* | 0.50 | 0.70 |
| Live Tank Circuit Breaker | All* | 0.50 | 0.70 |
| Current Transformer | All* | 0.50 | 0.70 |

* Damage state depends on the percentage of the subcomponents failing

**Table D.8.5: Damage Algorithms for Subcomponents of High Voltage Substations with Anchored Subcomponents (after G&E, 1994)**

| Peak Ground Acceleration | | | |
|---|---|---|---|
| **Classification** | **Damage State** | **Median (g)** | **β** |
| Transformer | All* | 0.40 | 0.70 |
| Disconnect Switches | All* | 0.60 | 0.70 |
| Live Tank Circuit Breaker | All* | 0.40 | 0.70 |
| Current Transformer | All* | 0.30 | 0.70 |

* Damage state depends on the percentage of the subcomponents failing

**Table D.8.6: Damage Algorithms for Subcomponents of High Voltage Substations with Unnchored Subcomponents**

| Peak Ground Acceleration | | | |
|---|---|---|---|
| **Classification** | **Damage State** | **Median (g)** | **β** |
| Transformer | All* | 0.25 | 0.70 |
| Disconnect Switches | All* | 0.40 | 0.70 |
| Live Tank Circuit Breaker | All* | 0.30 | 0.70 |
| Current Transformer | All* | 0.30 | 0.70 |

* Damage state depends on the percentage of the subcomponents failing

**Table D.8.7: Damage Algorithms for Distribution Circuits (after G&E, 1994)**

| Peak Ground Acceleration | | | |
|---|---|---|---|
| **Classification** | **Damage State** | **Median (g)** | **β** |
| Seismic | All* | 0.75 | 0.50 |
| Standard | All* | 0.60 | 0.50 |

* Damage state depends on the percentage of the subcomponents failing

**Table D.8.8: Damage Algorithms for Subcomponents of Generation Facilities with Anchored Subcomponents (after G&E, 1994)**

| Peak Ground Acceleration | | | |
|---|---|---|---|
| **Classification** | **Damage State** | **Median (g)** | **β** |
| Electrical Equipment | minor<br>moderate | 0.30<br>0.50 | 0.40<br>0.60 |
| Boilers & Pressure vessels | Moderate | 0.52 | 0.70 |
| Large vertical vessels with formed heads | Moderate<br>Extensive | 0.60<br>0.88 | 0.40<br>0.39 |
| Motor Driven Pumps | Extensive | 1.28 | 0.34 |
| Large horizontal vessels | Complete | 1.56 | 0.61 |
| Large motor operated valves | Complete | 1.93 | 0.65 |
| Boiler Building | minor<br>moderate<br>extensive<br>complete | 0.15<br>0.40<br>0.80<br>1.50 | 0.80<br>0.80<br>0.80<br>0.80 |
| Turbine Building | minor<br>moderate<br>extensive<br>complete | 0.15<br>0.40<br>0.80<br>1.50 | 0.80<br>0.80<br>0.80<br>0.80 |

**Table D.8.9: Damage Algorithms for Subcomponents of Generation Facilities with Unanchored Subcomponents (after G&E, 1994)**

| Peak Ground Acceleration | | | |
|---|---|---|---|
| **Classification** | **Damage State** | **Median (g)** | **β** |
| Electrical Equipment | minor<br>moderate | 0.22<br>0.35 | 0.50<br>0.70 |
| Boilers & Pressure vessels | Moderate | 0.36 | 0.70 |
| Large vertical vessels with formed heads | Moderate<br>Extensive | 0.46<br>0.68 | 0.50<br>0.48 |
| Motor Driven Pumps | Extensive | 1.00 | 0.43 |
| Large horizontal vessels | Complete | 1.05 | 0.75 |
| Large motor operated valves | Complete | 1.23 | 0.80 |
| Boiler Building | minor<br>moderate<br>extensive<br>complete | 0.15<br>0.40<br>0.80<br>1.50 | 0.80<br>0.80<br>0.80<br>0.80 |
| Turbine Building | minor<br>moderate<br>extensive<br>complete | 0.15<br>0.40<br>0.80<br>1.50 | 0.80<br>0.80<br>0.80<br>0.80 |

# APPENDIX 8E
# Subcomponent Damage Functions for Communication Systems

**Table E.8.1: Subcomponent Damage Algorithms for Communication Systems with Anchored Components**

| Peak Ground Acceleration | | | |
|---|---|---|---|
| **Subcomponents** | **Damage State** | **Median (g)** | **β** |
| Electric Power (Backup) | slight<br>moderate | 0.80<br>1.00 | 0.60<br>0.80 |
| Loss of commercial Power | minor<br>moderate | 0.15<br>0.30 | 0.40<br>0.40 |
| Switching Equipment | moderate<br>extensive<br>complete | 0.70<br>1.00<br>2.53 | 0.70<br>0.70<br>0.70 |
| Building | slight<br>moderate<br>extensive<br>complete | 0.15<br>0.40<br>0.80<br>1.50 | 0.80<br>0.80<br>0.80<br>0.80 |

**Table E.8.2: Subcomponent Damage Algorithms for Communication Systems with Unanchored Components**

| Peak Ground Acceleration | | | |
|---|---|---|---|
| **Subcomponents** | **Damage State** | **Median (g)** | **β** |
| Electric Power (Backup) | slight<br>moderate | 0.20<br>0.40 | 0.60<br>0.80 |
| Loss of commercial Power | minor<br>moderate | 0.15<br>0.30 | 0.40<br>0.40 |
| Switching Equipment | moderate<br>extensive<br>complete | 0.45<br>0.62<br>1.58 | 0.70<br>0.70<br>0.70 |
| Building | slight<br>moderate<br>extensive<br>complete | 0.15<br>0.40<br>0.80<br>1.50 | 0.80<br>0.80<br>0.80<br>0.80 |