Hazus Earthquake Model Technical Manual

Hazus 4.2 SP3

October 2020

U.S. Department of Homeland Security

FEMA

Table of Contents

List of Figures

List of Tables

Acronyms and Abbreviations

Acronym/ Abbreviation	Definition
AAL	Average Annualized Loss
AC	Alternating Current
AEBM	Advanced Engineering Building Module
AWSS	Auxiliary Water Supply System
C	Complete Damage
CalARP	California Accidental Release Prevention
CAPSS	City of San Francisco's Community Action Plan for Seismic Safety
CAS	Chemical Abstracts Service
CEUS	Central and Eastern United States
CGE	Computable General Equilibrium
CGS	California Geological Survey
CSM	Capacity Spectrum Method
DC	Direct Current
DS	Damage State
E	Extensive Damage
EBMUD	East Bay Municipal Utilities District
EOC	Emergency Operations Center
FEMA	Federal Emergency Management Agency
FFE	Fire Following Earthquake
ft	Feet
ft^2	Square Feet
GBS	General Building Stock
GF	Ground Failure
GIS	Geographic Information Systems
GNP	Gross National Product
GS	Ground Shaking
HC	High-Code
HH	Households
HIFLD	Homeland Infrastructure Foundation-Level Data
HPL	High Potential Loss
HS	Special High-Code
IELM	Indirect Economic Loss Module
I-O	Input-Output
km	Kilometer
LC	Low-Code
LS	Special Low-Code
LSI	Liquefaction Severity Index
M	Magnitude
M	Moderate Damage

Acronym/ Abbreviation	Definition
MC	Moderate-Code
MFU	Multi-Family Dwelling Units
MGD	Million Gallons per Day
MH	Mobile Homes
MMI	Modified Mercalli Intensity
MW	Megawatts
MS	Special Moderate-Code
N	Normal
NAICS	North American Industry Classification System
NBI	National Bridge Inventory
NBMG	Nevada Bureau of Mines and Geology
NEHRP	National Earthquake Hazards Reduction Program
NFPA	National Fire Protection Association
NGA	Next Generation Attenuation
NIBS	National Institute of Building Sciences
PC	Pre-code
PEH	Potential Earthquake Hazards
PGA	Peak Ground Acceleration
PGD	Permanent Ground Deformation
PGV	Peak Ground Velocity
psi	Pounds Per Square Inch
R	Reverse-slip
RR	Repair Rates
S	Slight Damage
SA	Spectral Acceleration
SDCWA	San Diego County Water Authority
sec	Second
SFD	Single-Family Dwellings
SFU	Single-Family Dwelling Units
SIC	Standard Industrial Classification
SRSS	Square Root of Summation of Squares
SS	Strike-slip
UDF	User-Defined Facilities
UNU	Uninhabitable Dwelling Units
USGS	U.S. Geological Survey
WUS	Western United States

Section 1. Introduction to the FEMA Hazus Loss Estimation Methodology

1.1 Background

The Hazus Earthquake Loss Estimation Methodology provides state, local, tribal, and territorial (SLTT) officials with a decision support software for estimating potential losses from earthquake events. This loss estimation capability enables users to anticipate the consequences of earthquakes and develop plans and strategies for reducing risk. The Geographic Information Systems (GIS)-based software can be applied to study geographic areas of varying scale with diverse population characteristics and can be implemented by users with a wide range of technical and subject matter expertise.

This Methodology has been developed, enhanced, and maintained by the Federal Emergency Management Agency (FEMA) to provide a tool for developing earthquake loss estimates for use in:

- Anticipating the possible nature and scope of the emergency response needed to cope with an earthquake-related disaster.
- Developing plans for recovery and reconstruction following a disaster.
- Mitigating the possible consequences of earthquakes.

The use of this standardized methodology provides nationally comparable estimates that allow the federal government to plan earthquake responses and guide the allocation of resources to stimulate risk mitigation efforts.

This *Hazus Earthquake Model Technical Manual* documents the methods used in calculating losses. A companion document, the *Hazus Inventory Technical Manual*, provides more detailed methodology and data descriptions for the inventory shared by each hazard model. Together, these documents provide a comprehensive overview of this nationally applicable loss estimation methodology.

The *Hazus Earthquake Model User Guidance* outlines the background and instructions for developing a Study Region and defining a scenario to complete an earthquake loss estimation analysis using Hazus. It also provides information on how to modify inventory, improve hazard data and analysis parameters for advanced applications, and guidance on calculating and interpreting loss results.

1.2 Hazus Uses and Applications

Hazus can be used by various types of users with a wide range of informational needs. A state, local, tribal, or territorial government official may be interested in the costs and benefits of specific mitigation strategies, and thus may want to know the expected losses if mitigation strategies have (or have not) been applied. Health officials may want information regarding the demands on medical care facilities, and may be interested in the number and severity of casualties for different earthquake scenarios. Emergency response teams may use the results of a loss study in planning and performing emergency response exercises. In particular, they might be interested in the operating capacity of emergency facilities such as fire stations, emergency operations centers, and police stations. Emergency planners may want estimates of temporary shelter requirements for different earthquake scenario events. Federal and state government agencies may conduct a loss analysis to obtain quick estimates of impacts in the hours immediately following an earthquake to best direct resources to the disaster area. Insurance companies may be interested in the estimated monetary losses so they can determine asset vulnerability.

Earthquake loss estimation analyses have a variety of uses for various departments, agencies, and community officials. As users become familiar with the loss estimation methodology, they are able to determine how to use it to best suit their needs and how to appropriately interpret the study results.

The products of Hazus analyses have several pre- and post-earthquake applications in addition to estimating the scale and extent of damage and disruption. Examples of pre-earthquake applications of the outputs include:

- Development of earthquake hazard mitigation strategies that outline policies and programs for reducing earthquake losses and disruptions indicated in the initial loss estimation study. Strategies can involve rehabilitation of hazardous existing buildings (e.g., unreinforced masonry structures), building code enforcement, development of appropriate zoning ordinances for land use planning in areas of liquefiable soils, and the adoption of advanced seismic building codes.
- Development of preparedness (contingency) planning measures that identify alternate transportation routes, planning earthquake preparedness, and education seminars.
- Anticipation of the nature and extent of response and recovery efforts including the identification of alternative housing, the location, availability and scope of required medical services, and the establishment of a priority ranking for restoration of water and power resources.

Post-earthquake applications of the outputs include:

- Projection of immediate economic impact assessments for state and federal resource allocation and support for state and/or federal disaster declarations by calculating direct economic impact on public and private resources, local governments, and the functionality of facilities in the area.
- Activation of immediate emergency recovery efforts including search and rescue operations, rapid identification and treatment of casualties, provision of emergency housing shelters, and rapid repair and availability of essential utility systems.
- Application of long-term reconstruction plans that include the identification of long-term reconstruction goals, implementation of appropriate wide-range economic development plans for the impacted area, allocation of permanent housing needs, and the assessment of land use planning principles and practices.

1.3 Assumed User Expertise

Users can be divided into two groups: those who perform the analysis and those who use the analysis’s results. For some analyses, these two groups occasionally consist of the same people, but generally this will not be the case. However, the more interaction that occurs between these two groups, the better the analysis will be. End users of the loss estimation analysis need to be involved from the beginning to make results more usable.

Any risk modeling effort can be complex and would benefit from input from an interdisciplinary group of experts. An earthquake loss analysis could be performed by a representative team consisting of the following:

- Geologists
- Geotechnical engineers
- Structural engineers
- Architects
- GIS specialists
- Economists
- Social scientists
- Emergency planners
- Policy makers

The individuals needed to perform the study can provide valuable insight into the risk assessment process. However, with the recent direct integration of probabilistic and deterministic earthquake ground motion data from the USGS into Hazus, defining earthquake hazard scenarios using authoritative data has become much easier. In addition to subject matter expert involvement, at least one GIS specialist should participate on the team.

If a state, local, tribal, or territorial agency is performing the analysis, some of the expertise may be found in-house. Experts are generally found in several departments: building permits, public works, planning, public health, engineering, information technologies, finance, historical preservation, natural resources, and land records. Although internal expertise may be most readily available, the importance of the external participation of individuals from academic institutions, citizen organizations, and private industry cannot be underestimated.

1.4 When to Seek Help

The results of a loss estimation analysis should be interpreted with caution because baseline values have a great deal of uncertainty. Baseline inventory datasets are the datasets that are provided with Hazus. Further information on these can be found in the Hazus Inventory Technical Manual. If the loss estimation team does not include individuals with expertise in the areas described above, it is advisable to retain objective reviewers with subject matter expertise to evaluate and comment on map and tabular data outputs.

If a seismologist is not available to assist in the selection of earthquake epicenter, magnitude, and other parameters, the user should defer to readily available ground motion data provided by the USGS. This will allow users to take advantage of USGS subject matter expertise when defining their probabilistic or deterministic earthquake scenario.

If the user intends to modify the baseline inventory data or parameters, assistance from an individual with expertise in the subject will be required. For example, if the user wishes to change percentages of specific building types for the region, collaborating with a structural engineer with knowledge of regional design and construction practices will be helpful. Similarly, if damage-motion relationships (fragility curves) need editing, input from a structural engineer will be required.

1.5 Technical Support

Technical Support contact information is provided in the Hazus application at **Help|Obtaining Technical Support**; technical assistance is available via the Hazus Help Desk by email at hazus-support@riskmapcds.com (preferred) or by phone at 1-877-FEMA-MAP (1-877-336-2627). The FEMA Hazus website also provides answers to Frequently Asked Questions, and information on software updates and training opportunities.

FEMA-provided resources also include the Hazus Virtual Training Library, a series of 21 short videos arranged into four playlists that cover various Hazus topics, from an introduction to Hazus methodologies, to targeted tutorials on running Hazus analyses, to best practices when sharing results with decision makers. This easily accessible learning material provides quick topic-refreshers, free troubleshooting resources, and engaging guides to further Hazus exploration.

The application's **Help** menu references the help files for ArcGIS. Since Hazus was built as an extension to ArcGIS functionality, knowing how to use ArcGIS and ArcGIS Help Desk will help Hazus users.

Technical support on any of the four hazards is available at the contacts shown via **Help|Obtaining Technical Support**.

1.6 Uncertainties in Loss Estimates

Although the Hazus software offers users the opportunity to prepare comprehensive loss estimates, it should be recognized that uncertainties are inherent in any estimation methodology, even with state-of-the-art techniques. Any region or city studied will have an enormous variety of buildings and facilities of different sizes, shapes, and structural systems that have been built over a range of years, under diverse seismic design codes. There are a variety of components that contribute to transportation and utility system damage estimations and these components can have differing seismic resistance.

Due to this complexity, there is inherent uncertainty in modeling the structural resistance of most buildings and other facilities. Further, there are not sufficient data from past earthquakes or laboratory experiments to determine precise estimates of damage based on known ground motions, even for specific buildings and other structures. To deal with this complexity and lack of data, buildings and components of systems are grouped into categories based upon key characteristics. The relationships between key features of ground shaking and average degree of damage with associated losses for each building category are based on current data and available theories.

The results of an earthquake loss analysis should not be looked upon as a prediction. Instead, they are only an estimate, as uncertainty inherent to the model will be influenced by quality of inventory data and the hazard parameters. This is particularly true in areas where seismic events are infrequent or where recorded data is scarce.

Section 2. Introduction to Earthquake Loss Estimation Methodology

This brief overview of the Earthquake Methodology is intended for state, local, tribal, and territorial officials contemplating an earthquake loss analysis.

The Hazus Methodologies will generate an estimate of the consequences of a scenario or probabilistic earthquake event to a city, county, or region. The resulting "loss estimate" will generally describe the scale and extent of damage and disruption that may result from the modeled earthquake event. The following information can be obtained:

- *Quantitative estimates of losses* in terms of direct costs for repair and replacement of damaged buildings and transportation and utility system components, direct costs associated with loss of function (e.g., loss of business revenue, relocation costs), casualties, household displacements, quantity of debris, and regional economic impacts.
- *Functionality losses* in terms of loss of function and restoration times for essential facilities such as hospitals and components of transportation and utility systems, and simplified analyses of loss-of-system-function for electrical distribution and potable water systems.
- *Extent of induced hazards* in terms of exposed population and building value due to potential fire following earthquake.

To generate this information, the Methodology includes:

- Classification systems used in assembling inventory and compiling information on the General Building Stock (GBS), the components of transportation and utility systems, and demographic and economic data.
- Standard calculations for estimating type and extent of damage and for summarizing losses.
- National and regional databases containing information for use as baseline (built-in) data useable in the calculation of losses if there is an absence of user-supplied data.

These systems, methods, and data have been combined in a user-friendly GIS software for this loss estimation application.

The Hazus software uses GIS technologies for performing analyses with inventory data and displaying losses and consequences on applicable tables and maps. The Methodology permits estimates to be made at several levels of complexity, based on the level of inventory data entered for the analysis (i.e., baseline data versus locally enhanced data). The more concise and complete the inventory information, the more accurate the results.

The following figure provides a graphic representation of the modules that the Hazus Earthquake Model Methodology is comprised of, and their interrelation in deriving estimates.

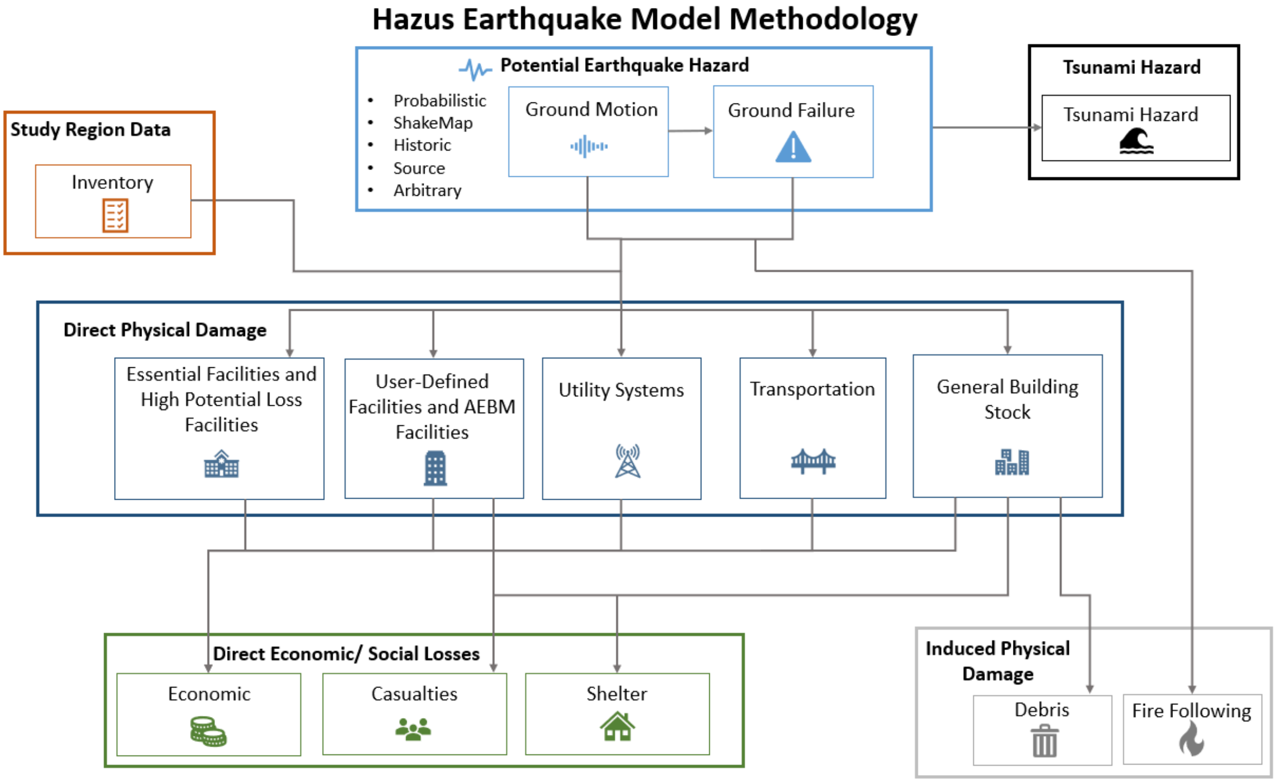


Figure 2-1 Hazus Earthquake Model Methodology Schematic

While Figure 2-1 shows the conceptual relationships, the steps used in the Hazus Earthquake Model are as follows:

- *Select the area to be studied*. The Hazus Study Region (the region of interest) is created based on Census tract, county, or state level aggregation of data. The area generally includes a city, county, or group of municipalities. It is generally desirable to select an area that is under the jurisdiction of an existing regional planning group.
- *Specify the earthquake hazard scenario*. In developing the scenario earthquake, consideration should be given to credible earthquake sources and potential fault locations using the USGS and Hazus datasets, or subject matter experts.
- *Provide information on local soil and geological conditions, if available*. Soil characteristics include site classification according to the National Earthquake Hazard Reduction Program (NEHRP) and susceptibility to landslides and liquefaction.
- *Integrate local inventory data*. Include essential facilities, transportation and utility systems, updates to GBS characteristics, user-defined facilities, or Advanced Engineering Building Module (AEBM) structures.
- *Use the formulas embedded in Hazus*. Compute probability distributions for damage to different classes of buildings, facilities, and infrastructure system components. Then, estimate the loss of function.
- *Compute estimates of direct economic loss, casualties and shelter needs using the damage and functionality information*.
- *Estimate fire risks following earthquake impacts*, such as the number of ignitions and extent of fire spread.

- *Estimate the amount and type of debris*.

The user plays a major role in selecting the scope and nature of the output of a loss estimation analysis. A variety of maps can be generated for visualizing the extent of the losses. Generated reports provide numerical results that may be examined at the level of the Census tract or aggregated by county or region.

2.1 Earthquake Hazards Considered in the Methodology

The earthquake-related hazards considered by the Hazus Methodology in evaluating damage, resultant losses, and casualties are collectively referred to as potential earthquake hazards (PEH). Most damage and loss caused by an earthquake is directly or indirectly the result of ground shaking. Thus, Hazus evaluates the geographic distribution of ground shaking as a result of a specific earthquake scenario and expresses ground shaking using several quantitative parameters (e.g., peak ground acceleration, spectral acceleration).

The following three features of earthquakes can cause permanent ground displacements and have an adverse effect on structures, roadways, pipelines, and other infrastructure system structures:

- *Fault rupture*: Ground shaking is caused by fault rupture, usually below the ground surface. However, fault rupture can reach the surface of the earth as a narrow zone of ground offsets and tear apart structures and pipelines in this zone.
- *Liquefaction*: This occurs when loose, water-saturated soils are shaken strongly and causes sudden loss of strength and stiffness in soils. This shaking can lead to settlement and horizontal movements of the ground.
- *Landslides*: Large downhill movement of soil or rock that is shaken free from hillsides or mountainsides during an earthquake event and can destroy anything in its path.

Soil type can have a significant effect on the intensity of ground motion at a particular site. Soil, as defined in this methodology, is classified in terms of geology. The quality of analysis is significantly reduced if soil amplification is not considered. Hazus now incorporates soil amplification provided by the USGS in the probabilistic ground motions. In addition, when using the USGS ShakeMap input for actual earthquakes or scenarios, site soil amplification is already included. The software contains several additional options for determining the effect of soil type on ground motions for a given magnitude and location. The user may opt to use the baseline soil classification or provide their own soil layer.

2.2 Definitions of Structures

There are differences between terminology used to designate distinctions between types or categories of structures. The term “structure” refers to all constructions, such as a building, bridge, water tank, shed, carport, or other man-made thing that is at least semi-permanent. A building is a structure with a roof and walls that is intended for use by people and/or inventory and contents, such as a house, school, office, or commercial storefront. A facility corresponds to a particular place, generally a building, with an intended purpose such as a school, hospital, electric power station, or water treatment facility. Some facilities are defined as ‘essential facilities’ meaning the facility is critical to maintaining services and functions vital to a community, especially during disaster events. The buildings, essential facilities, and transportation and utility systems considered by the Methodology are as follows:

- *General Building Stock:* The key General Building Stock (GBS) databases in Hazus include square footage by occupancy and building type, building count by occupancy and building type, building and content valuation by occupancy and building type, and general occupancy mapping. Most of the commercial, industrial, and residential buildings in a region are not considered individually when calculating losses. Buildings within each Census tract are aggregated and categorized. Building information derived from Census and employment data are used to form groups of 36 specific building types and 33 occupancy classes (additional information on the Hazus baseline GBS inventory data is provided in the Hazus Inventory Technical Manual). Degree of damage is computed for each grouped combination of specific building type and occupancy class.
- *Essential facilities:* Essential facilities are the facilities that are vital to emergency response and recovery following a disaster. These facilities can include, but are not limited to, medical care facilities, emergency response facilities, and schools. For this class of structures, damage and loss-of-function are evaluated on a building-by-building basis. There may be significant uncertainties in each estimate.
- *Transportation systems:* Transportation systems, (including highways, railways, light rail, bus systems, ports, ferry systems, and airports) are classified into components such as bridges, stretches of roadway or track, terminals, and port warehouses. Probabilities of damage and losses are computed for each component of each system, but total system performance is not evaluated.
- *Utility systems:* Utility systems, including potable water, electric power, wastewater, communications, and liquid fuels (oil and gas), are treated in a manner similar to transportation systems. Probabilities of damage and losses are computed for each component of each system, and simplified methods allow for the estimation of approximate system outage (i.e., total households without potable water or electricity), but detailed system performance is not evaluated, nor are cascading impacts from one system to another.
- *High potential loss facilities:* In any region or community, there will be certain types of structures or facilities for which damage and losses will not be (reliably) evaluated without facility-specific supplemental studies. These facilities include dams and levees, nuclear power plants, and military installations.

Specific data can be used to estimate potential damage and hazard effects using the User-Defined Facilities (UDF) module and the Advanced Engineering Building Module (AEBM), which are addressed in the *Earthquake Model User Guidance* and the *AEBM Technical and User's Manual*.

2.3 Levels of Analysis

Hazus is designed to support two general types of analysis (Basic and Advanced), split into three levels of data updates (Levels 1, 2, and 3). Figure 2-2 provides a graphic representation of the various levels of analysis.

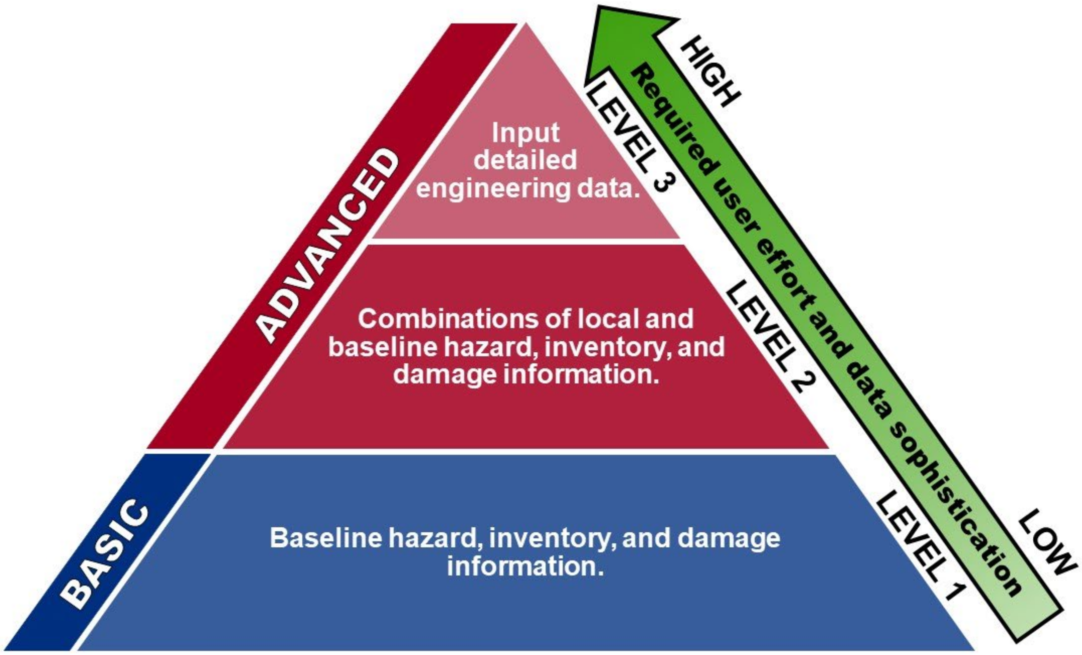


Figure 2-2 Levels of Hazus Analysis

2.3.1 Analysis Based on Baseline Information

The basic level of analysis uses only the baseline databases built into the Hazus software and Methodology on building square footage and value, population characteristics, costs of building repair, and certain basic economic data. This level of analysis is commonly referred to as a Level 1 analysis. In a basic analysis (Level 1), one average soil condition is assumed for the entire Study Region. The effects of possible liquefaction and landslide hazards are ignored. Direct economic and social losses associated with the GBS and essential facilities are computed. Baseline data for transportation and utility systems are included; thus, these systems are considered in the basic level of analysis. However, there is a significant level of uncertainty pertaining to the estimates.

Other than defining the Study Region, selecting the scenario earthquake(s), and making decisions concerning the extent and format of the output, an analysis based on baseline data requires minimal effort from the user. As indicated, the estimates involve large uncertainties when inventories are limited to the baseline data. This level of analysis is suitable primarily for preliminary evaluations and crude comparisons among different Study Regions with a Census tract as the smallest regional unit. A basic Level 1 analysis could be used for comparisons and preliminary evaluations to assist in identifying potential mitigation actions within a community, which could be useful if evaluating funding priority for projects.

2.3.2 Analysis with User Supplied Inventory

Results from an analysis using only baseline inventory data can be improved greatly with at least a minimum amount of locally developed input. Improved results are highly dependent on the quality and quantity of improved inventory data. The significance of the improved results also relies on the user’s analysis priorities. This level of advanced analysis is commonly referred to as a Level

2/Level 3 analysis. The following inventory improvements impact the accuracy of Level 2/Level 3 Advanced Analysis results:

- Development of maps of soil conditions affecting ground shaking, liquefaction and landslide potential. These maps, if available, are used for evaluating the effects of these local conditions on damage and losses.
- Use of locally available data or estimates of the square footage of buildings in different occupancy classes.
- Use of local expertise to modify the mapping scheme databases that determine the percent-ages of specific building types associated with different occupancy classes.
- Preparation of a detailed inventory of all essential facilities.
- Collection of detailed inventory and cost data to improve evaluation of losses and lack of function in various transportation and utility systems.
- Use of locally available data concerning construction costs or other economic parameters.
- Compilation of information concerning high potential loss facilities.
- Collection of data, such as number of fire trucks, for evaluating the probable extent of areas affected by post-earthquake fires.

Section 3. Inventory

The technical guidance related to inventory data associated with the Hazus Earthquake Methodology and software is detailed in the *Hazus Inventory Technical Manual*. The *Hazus Inventory Technical Manual* describes the classification of different buildings and infrastructure systems, data, and attributes required for performing damage and loss estimation, and the data supplied with the Hazus software.

Section 4. Potential Earthquake Hazards (PEH)

Potential Earthquake Hazards (PEH) related to earthquakes include ground motion and ground failure (i.e., liquefaction, landslide, and surface fault rupture). Methods for developing estimates of ground motion and ground failure are discussed in the sections that follow.

4.1 Ground Motion

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

- Deterministic ground motion maps (ShakeMap data are the preferred data source recommended for deterministic earthquakes - both actual and hypothetical - by FEMA and the USGS National Earthquake Information Center)
- USGS probabilistic ground motion maps (maps supplied within Hazus)
- Other probabilistic or deterministic ground motion maps (user-supplied maps)

With USGS ShakeMaps now available in Hazus for both actual and scenario events through a direct data integration feed, the utilization of USGS ShakeMaps is the primary recommended source for deterministic hazard data to use in Hazus. Hazus incorporates an online interface to retrieve both actual earthquake and scenario ShakeMaps directly from the USGS. USGS ShakeMaps for actual earthquake events incorporate ground motion recordings from instrumentation, earthquake source parameters developed by a seismologist, as well as felt earthquake report data. USGS ShakeMaps for scenario earthquakes are developed by the scientific community and incorporate the latest science in terms of ground motion modeling, as well as site soil amplification. Further, the entire set of available Hazus building fragility functions have been specifically calibrated for use with ShakeMap as the input ground motion data. With the Hazus integration of the ShakeMap grid, ground motion data are area weighted and averaged across each Census tract.

In areas where ShakeMap scenarios are limited, several legacy options are available to model ground motions within Hazus, including defining the scenario as a historic epicenter event, a source event and an arbitrary event, and calculating ground motions using attenuation relationships or ground motion prediction equations. Hazus includes 49 attenuation functions for the western United States, and ten attenuation relationships for the eastern United States. It should be noted, however, that these attenuation functions have not been updated since 2008.

In the Hazus Methodology's probabilistic analysis procedure, the ground shaking demand is characterized by spectral contour maps developed by the USGS as part of the 2014 update of the National Seismic Hazard Maps. USGS probabilistic seismic hazard maps are revised every six years to reflect newly published or thoroughly reviewed earthquake science to stay current with regular updates of building codes.

The Hazus Methodology includes maps for eight probabilistic hazard levels ranging from ground shaking with a 39% probability of being exceeded in 50 years (100-year return period) to the ground shaking with a 2% probability of being exceeded in 50 years (2500-year return period). The probabilistic hazard data supplied with Hazus is provided in two versions:

- *Probabilistic ground motions including soil amplification*: Users with no user-supplied soils data will automatically use the amplified version of the USGS probabilistic ground motion data, amplified using the new site soil characterization based on USGS 2016 Vs30 data (the average shear wave velocity of the upper 30 meters of soil) now available for probabilistic scenarios (see FEMA P- 366 USGS NEIC methodology (FEMA, 2017)).
- *Probabilistic ground motions without soil amplification*: Users with custom/user-supplied soils data will use the original (non-amplified) USGS 2016 probabilistic ground motion grid and Hazus will apply National Earthquake Hazard Reduction Program (NEHRP) soil amplification to ground motions based on the user's soil map data.

Both options are an improvement upon the previous implementation, where all probabilistic ground motion data were amplified assuming the overly conservative Type D (soft soil) category.

User-supplied PGA and spectral acceleration contour maps may also be used with Hazus. In this case, the user must provide all contour maps in a pre-defined digital format (as specified in the *Hazus Earthquake User Guidance*). The Hazus Methodology assumes that user-supplied ground motion maps already include soil amplification.

4.1.1 Form of Ground Motion Estimates/Site-Effects

Ground motion estimates are represented by (1) contour maps and (2) location-specific values of ground shaking demand, which are generally used to compute earthquake losses. For the general building stock, ground motion demand is averaged over each Census tract. However, contour maps can also be developed to provide pictorial representations of the variation in ground motion demand within the Study Region. When ground motion is based on either USGS ShakeMaps or user-supplied maps, location-specific values of ground shaking demand are extracted based on the underlying PGA, PGV or spectral acceleration (SA) values, respectively.

For the analysis of building damage, three ground motion parameters are used: PGA, SA at 0.3 seconds, and SA at 1.0 second. These values define the shape of a standard elastic response spectrum (see Section 4.1.3.2), with PGA representing the y-intercept, SA at 0.3 seconds representing the acceleration domain, and SA at 1.0 seconds representing the velocity domain. PGV is used in the analysis of pipeline damage.

4.1.2 Input Requirements and Output Information

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

- *Scenario Basis* - The user must select the basis for determining ground shaking demand from one of three options: (1) deterministic data, including USGS ShakeMaps, (2) probabilistic data supplied by the Methodology, or (3) user-supplied maps.
- *Attenuation Relationship* - For a deterministic calculation of ground shaking in areas where USGS ShakeMaps availability is limited, the user selects an appropriate attenuation relationship from those supplied with the Methodology. Attenuation relationships are based on the geographic location of the Study Region (Western United States (WUS) vs. Central and Eastern United States (CEUS)) and on the type of fault for WUS sources. WUS regions include locations in, or west of, the Rocky Mountains, Hawaii, and Alaska. Figure 4-1 the regional separation of WUS and CEUS locations as defined by the USGS in the development of the National Seismic Hazard Maps. For WUS sources, the attenuation functions predict ground shaking based on source type, including: (1) strike-slip (SS) faults,

(2) reverse-slip (R) faults, (3) normal (N) faults (4) Interface events and (5) Interslab events. The Methodology provides combinations of attenuation functions for the WUS and CEUS, respectively, where the default weights are consistent with those used in compiling the 2008 USGS probabilistic data (Petersen et al., 2008). The weighted functions for the 2008 update consisted of the latest Next Generation Attenuation (NGA) functions for the WUS that are also included in Hazus, however, the NGA functions for the CEUS were not yet available for the 2008 weighting or Hazus at that time. As a result, the Hazus attenuation functions for the CEUS are generally older than the WUS (1996-2006).

- *Soil Map* – For non-ShakeMap deterministic scenarios, the user may supply a detailed soil map to account for local site soil conditions. This map must identify soil type using a scheme that is based on, or can be related to, the site class definitions of the 1997 NEHRP Provisions, and must be in pre-defined digital format (as specified in the *Hazus Earthquake User Guidance*). In the absence of a soil map, Hazus will amplify the ground motions assuming Site Class D soil at all locations. The user can also modify the assumed uniform Site Class soil type by modifying the analysis parameters in Hazus (i.e., change the Site Class from D to A, B, C, or E).

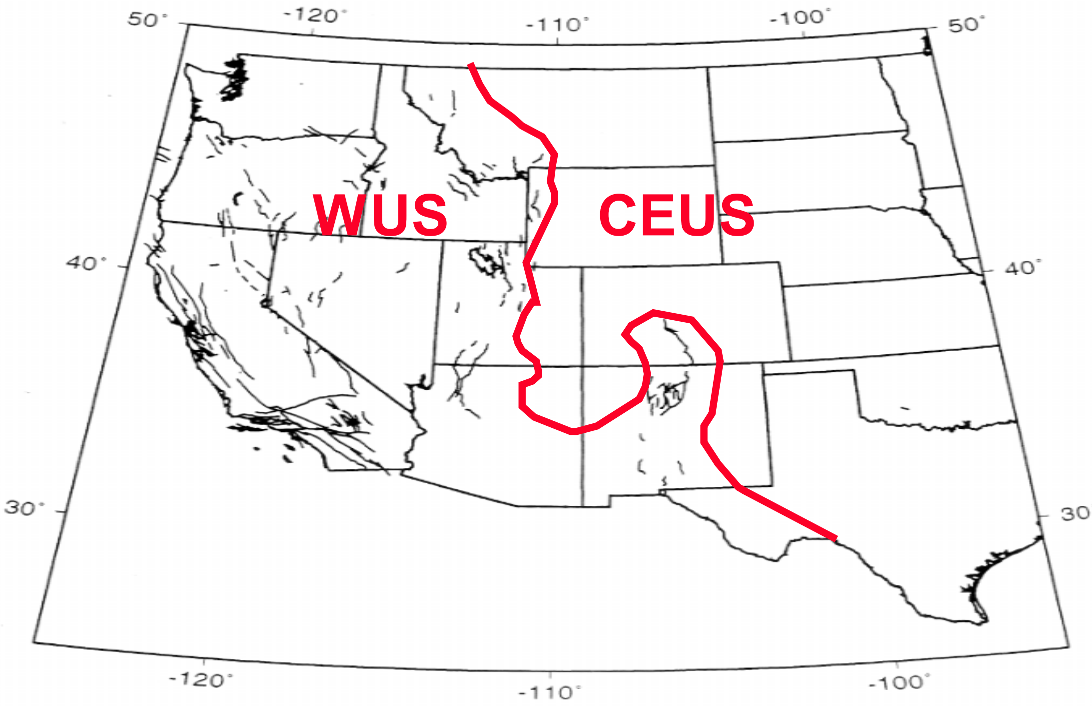


Figure 4-1 Boundaries Between WUS and CEUS Locations

4.1.3 Description of Methods

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

- Basis for ground shaking (Section 4.1.3.1)
- Standard shape of response spectra (Section 4.1.3.2)
- Attenuation of ground shaking (Section 4.1.3.3)
- Distance measurement used with attenuation relationships (Section 4.1.3.4)
- Amplification of ground shaking for local site conditions (Section 4.1.3.5)

4.1.3.1 Basis for Ground Shaking

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

- Deterministic hazards for scenario earthquakes – use of USGS ShakeMaps or calculation of scenario earthquake ground shaking
- Probabilistic seismic hazard maps (USGS)
- User-supplied seismic hazard maps

4.1.3.1.1 Use of USGS ShakeMaps

ShakeMap is a product of the USGS Earthquake Hazards Program in partnership with regional seismic networks and leverages additional localized data. ShakeMap provides near-real-time maps and digital data of ground motion and shaking intensity following significant earthquakes. The loss estimates identified after running analyses using ShakeMap data in Hazus can help emergency personnel respond appropriately in areas of immediate need. Federal, state, and local agencies, as well as non-profit organizations use these maps for post-earthquake response and recovery, public and scientific information, preparedness exercises, and disaster planning.

A ShakeMap is a representation of ground shaking produced by an earthquake. The information it presents is different from the earthquake magnitude and epicenter that are released after an earthquake because ShakeMap focuses on the ground shaking produced by the earthquake, rather than the parameters describing the earthquake source. So, while an earthquake has one magnitude and one epicenter, it produces a range of ground shaking levels at sites throughout the region depending on distance from the earthquake, the rock and soil conditions at sites, and variations in the propagation of seismic waves from the earthquake due to complexities in the structure of the Earth’s crust. Comprehensive scientific information for these maps can be found at the USGS ShakeMap website.

Hazus allows users to directly import USGS ShakeMap products for both actual earthquakes and for scenario earthquakes, or to access previously downloaded ShakeMap grid data. Refer to the *Hazus Earthquake User Guidance* for additional details.

4.1.3.1.2 Deterministic Calculation of Scenario Earthquake Ground Shaking

For the calculation of ground motions from a deterministic (scenario) event, the user specifies the location (e.g., epicenter) and moment magnitude of the scenario earthquake. The Methodology provides three options for selection of an appropriate scenario earthquake location. The user can either: (1) specify an event based on a database of WUS seismic sources (faults), (2) specify an event based on a database of historical earthquake epicenters, or (3) specify an event based on an arbitrary choice of the epicenter. These options are described below.

4.1.3.1.2.1 Seismic Source Database (WUS Fault Map)

For the WUS, the Methodology provides a database of seismic sources (fault segments) developed by the USGS, the California Geological Survey (CGS) and the Nevada Bureau of Mines and Geology (NBMG). The user accesses the database map (using Hazus) and selects a moment magnitude and epicenter on one of the identified fault segments. The database includes information on fault segment type, location, orientation, and geometry (e.g., depth, width, and dip angle), as well as on each fault segment’s seismic potential (e.g., maximum moment).

The Methodology computes the expected values of surface and subsurface fault rupture length. Fault rupture length is based on the relationship of Wells and Coppersmith (1994) given in Equation 4-1, using the coefficient values given in Table 4-1 below:

Equation 4-1

$$\log_{10}(\mathrm{L}) = \mathrm{a} + \mathrm{b} * \mathbf{M}$$

Where:

L is the rupture length (km)

M is the moment magnitude of the earthquake

Table 4-1 Regression Coefficients of Fault Rupture Relationship

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

Fault rupture is assumed to be of equal length on each side of the epicenter, provided the calculated rupture length is available in both directions along the specified fault segment. If the epicenter location is less than one-half of the rupture length from an end point of the fault segment (e.g., the epicenter is located at or near an end of the fault segment), then fault rupture length is truncated so that rupture does not extend past the end of the fault segment. If the calculated rupture length exceeds the length of the fault segment, then the entire fault segment is assumed to rupture between its end points.

4.1.3.1.2.2 Historical Earthquake Database (Epicenter Map)

Hazus provides a database of historical earthquakes that were utilized in the development of the 2008 USGS national earthquake hazard maps (Petersen et al., 2008) and contains over 6,000 records. The database has been sorted to remove historical earthquakes with magnitudes less than 5.0. The user accesses the database via Hazus and selects a historical earthquake epicenter which includes location, depth, and magnitude information.

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

4.1.3.1.2.3 Arbitrary Event

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

4.1.3.1.3 Probabilistic Seismic Hazard Maps (USGS)

The Methodology includes probabilistic seismic hazard data developed by the USGS for the 2014 update of the National Seismic Hazard Maps (Petersen et al., 2014). It should be noted that older data are still used for Alaska (2007, see: Wesson et al., 2007), Hawaii (1998, see: Klein et al.,1998 and Klein et al., 2001), and Puerto Rico and the U.S. Virgin Islands (2003, see Mueller et al., 2010). The USGS maps provide estimates of PGA and spectral acceleration at periods of 0.1, 0.2, 0.3, 0.75, 1.0, 2.0, 3.0, 4.0, and 5.0 seconds and for different exceedance probabilities (return periods). In Hazus, only PGA and spectral acceleration at periods of 0.3 second and 1.0 second are used. Ground shaking estimates have been extracted for eight exceedance probabilities (return periods), ranging from ground shaking with a 39% probability of being exceeded in 50 years (100 year return period) to a 2% probability of being exceeded in 50 years (2,500 year return period).

4.1.3.1.4 User-Supplied Seismic Hazard Maps

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

If only PGA contour maps are available, the user must develop the other required maps. One approach that can help achieve that is to use the spectral acceleration response factors given later in Table 4-2.

4.1.3.2 Standard Shape of the Response Spectra

The Methodology characterizes ground shaking using a standardized response spectrum shape, as shown in Figure 4-2. The standardized shape consists of four parts: peak ground acceleration (PGA), a region of constant spectral acceleration at periods from zero seconds to T_{AV} (seconds), a region of constant spectral velocity at periods from T_{AV} to T_{VD} (seconds) and a region of constant spectral displacement for periods of T_{VD} and beyond. In Figure 4-2, spectral acceleration is plotted as a function of spectral displacement (rather than as a function of period). This is the format of response spectra used for evaluation of damage to buildings and essential facilities.

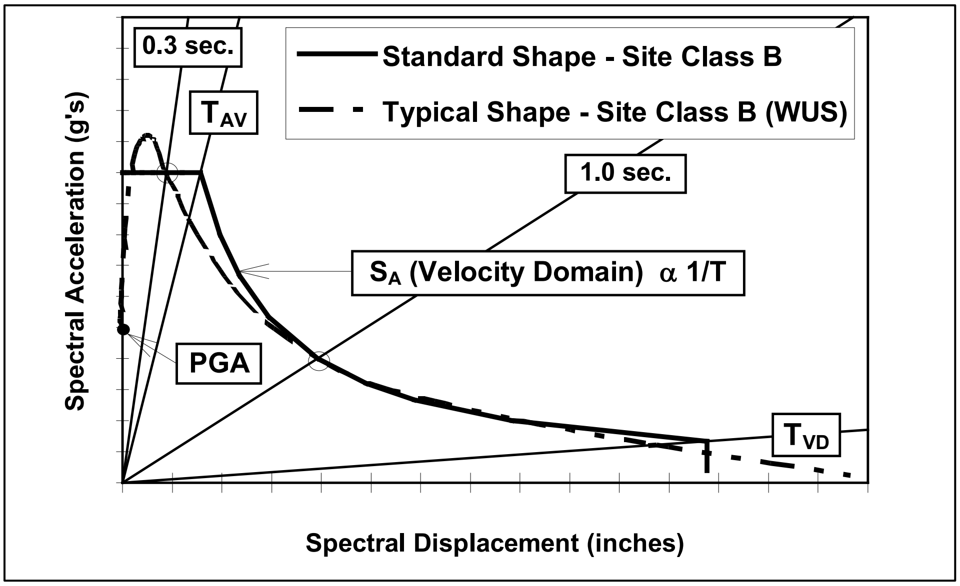


Figure 4-2 Standardized Response Spectrum Shape

Equation 4-2 may be used to convert spectral displacement (inches), to period (seconds) for a given value of spectral acceleration (units of g), and Equation 4-3 may be used to convert spectral acceleration (units of g) to spectral displacement (inches) for a given value of period.

Equation 4-2

$$T = 0.32\sqrt{\frac{S_D}{S_A}}$$

Equation 4-3

$$S_D = 9.8 * S_A * T^2$$

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

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

Equation 4-4

$$T_{VD} = 1/f_c = 10^{[(M-5)/2]}$$

When the moment magnitude of the scenario earthquake is not known (e.g., when using user-supplied maps), the period T_{VD} is assumed to be 10 seconds (i.e., the moment magnitude is assumed to be **M** = 7.0). However, Hazus requires the magnitude driving the ground motions supplied in the USGS ShakeMap, user-supplied maps or the USGS probabilistic ground motions in order to estimate duration of shaking as described in Section 5.

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

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

4.1.3.2.1 Inferred Ground Shaking Hazard Information

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

- PGV is inferred from 1-second spectral acceleration response
- Spectral acceleration response is inferred from PGA
- 0.3-second spectral acceleration response is inferred from 0.2-second response

4.1.3.2.1.1 PGV Inferred from 1-Second Spectral Response

Unless supplied by the user (i.e., as user-supplied PGV maps), peak ground velocity (inches per second) is inferred from 1-second spectral acceleration, SA1 (units of g), using Equation 4-5.

Equation 4-5

$$\mathrm{PGV} = \left(\frac{386.4}{2\pi} * \mathrm{S_{A1}}\right) / 1.65$$

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

4.1.3.2.1.2 Spectral Acceleration Response Inferred from PGA

When a user has maps of PGA only, spectral acceleration for the short periods, SA_S, maps are developed from PGA, and spectral acceleration for the long period, SA_L, is inferred from short period spectral acceleration, SAS, based on the factors given in Table 4 2 for WUS and CEUS rock (Site Class B) locations.

The factors given in Table 4-2 are based on the combination attenuation functions for WUS and CEUS events. These factors distinguish between small-magnitude and large-magnitude events and between sites that are located at different distances (i.e., CUES: distance to hypocenter and

WUS: distance to fault rupture plane). The ratios of SA_S/SA_L and SA_S/PGA define the standard shape of the response spectrum for each of the magnitude/distance combinations of Table 4-2.

Table 4-2 requires magnitude and distance information to determine spectrum amplification factors. This information would likely be available for maps of observed earthquake PGA, or scenario earthquake PGA, but is not available for probabilistic maps of PGA since probabilistic maps are aggregated estimates of seismic hazard due to different event magnitudes and sources.

Table 4-2 Spectral Acceleration Response Factors

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

4.1.3.2.1.3 0.3-Second Spectral Acceleration Response Inferred from 0.2-Second Response

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

4.1.3.3 Attenuation of Ground Shaking

Ground shaking is attenuated with distance from the source using relationships provided with the Methodology. Table 4-3 lists the 59 ground motion prediction equations used by Hazus to model ground motions and identifies the applicable region(s), the different types of faulting modeled, and the fault distance parameter used by each function. The table also identifies relationships as primary (stand-alone) or dependent (combination functions, see Table 4-4), and whether hanging-wall effects are considered. It should be noted that the Hazus attenuation functions have not been updated since 2008, so the use of USGS ShakeMaps is strongly recommended. The suite of available relationships does include several of the initial “Next Generation of Ground-Motion Attenuation Models” (NGA) for the western United States, identified in Table 4-3 by the “NGA” in the description. However, the relationships developed under the subsequent NGA-West2 and NGA-East programs were not yet available when this update was made to Hazus. Since the initial NGA updates in Hazus, development has been focused towards the integration of authoritative external ground motions products available from the USGS.

Table 4-3 Summary List of Attenuation Relationships

No.	Description	Fault Type	Region	Distance Measure*	Primary (P) or Dependent (D)**	Considers Hanging Wall Effects (Y/N)
1	Toro et al. (1997)	Shallow	CEUS	R_{JB}	P	N
2	Frankel (1996)	Shallow	CEUS	R_{JB}	P	N
3	Campbell (2003)	Shallow	CEUS	R_{JB}	P	N
4	Atkinson and Boore (2006)	Shallow	CEUS	R_{JB}	P	N
5	Tavakoli & Pezeshk (2005)	Shallow	CEUS	R_{JB}	P	N
6	Silva et al. (2002)	Shallow	CEUS	R_{JB}	P	N
7	Somerville (2002)	Shallow	CEUS	R_{JB}	P	N
8	NGA - Boore & Atkinson (2008	Strike-slip	WUS	R_{JB}	P	Y
9	NGA - Boore & Atkinson (2008)	Reverse	WUS	R_{JB}	P	Y
10	NGA - Boore & Atkinson (2008)	Normal	WUS	R_{JB}	P	Y
11	NGA - Chiou & Youngs (2008)	Strike-slip	WUS	R_{RUP}	P	Y
12	NGA - Chiou & Youngs (2008)	Reverse	WUS	R_{RUP}	P	Y
13	NGA - Chiou & Youngs (2008)	Normal	WUS	R_{RUP}	P	Y
14	NGA - Campbell & Bozorgnia (2008)	Strike-slip	WUS	R_{RUP}	P	Y
15	NGA - Campbell & Bozorgnia (2008)	Reverse	WUS	R_{RUP}	P	Y
16	NGA - Campbell & Bozorgnia (2008)	Normal	WUS	R_{RUP}	P	Y
17	NGA - Abrahamson & Silva (2008)	Strike-slip	WUS	R_{RUP}	P	N
18	NGA - Abrahamson & Silva (2008)	Reverse	WUS	R_{RUP}	P	N
19	NGA - Abrahamson & Silva (2008)	Normal	WUS	R_{RUP}	P	N
20	Cascadia - Youngs et al. (1997)	Interslab	WUS	R_{RUP}	P	N
21	Cascadia - Youngs et al. (1997)	Interface	WUS	R_{RUP}	P	N
22	Atkinson & Boore, Global (2002)	Interslab	WUS	R_{RUP}	P	N
23	Atkinson & Boore, Global (2002)	Interface	WUS	R_{RUP}	P	N
24	Atkinson & Boore (2002), Regional	Interslab	WUS	R_{RUP}	P	N
25	Atkinson & Boore (2002), Regional	Interface	WUS	R_{RUP}	P	N
26	Zhao and Others (2006)	Interslab	WUS	R_{HYPO}	P	N
27	Zhao and Others (2006)	Interface	WUS	R_{HYPO}	P	N
28	Central & East US (CEUS 2008)	Shallow	CEUS	-	D	N
29	CEUS, New Madrid Seismic Zone (NMSZ 2008)	Shallow	CEUS	-	D	N
30	CEUS, Charleston 2008	Shallow	CEUS	-	D	N
31	West US, Coastal California 2008	Strike-slip	WUS	-	D	N
32	West US, Coastal California 2008	Reverse	WUS	-	D	N
33	West US, Coastal California 2008	Normal	WUS	-	D	N
34	West US, Extensional 2008	Strike-slip	WUS	-	D	N
35	West US, Extensional 2008	Reverse	WUS	-	D	N
36	West US, Extensional 2008	Normal	WUS	-	D	N

No.	Description	Fault Type	Region	Distance Measure*	Primary (P) or Dependent (D)**	Considers Hanging Wall Effects (Y/N)
37	West US, Non-Extensional 2008	Strike-slip	WUS	-	D	N
38	West US, Non-Extensional 2008	Reverse	WUS	-	D	N
39	West US, Non-Extensional 2008	Normal	WUS	-	D	N
40	West US, inter-Mountain West	Strike-slip	WUS	-	D	N
41	West US, inter-Mountain West	Reverse	WUS	-	D	N
42	West US, inter-Mountain West	Normal	WUS	-	D	N
43	West US, Wasatch 2008	Strike-slip	WUS	-	D	N
44	West US, Wasatch 2008	Reverse	WUS	-	D	N
45	West US, Wasatch 2008	Normal	WUS	-	D	N
46	Pacific Northwest (PNW 2008)	Strike-slip	WUS	-	D	N
47	Pacific Northwest (PNW 2008)	Reverse	WUS	-	D	N
48	Pacific Northwest (PNW 2008)	Normal	WUS	-	D	N
49	Cascadia - Subduction (2008)	Interface	WUS	-	D	N
50	Cascadia – Subduction (2008)	Interslab	WUS	-	D	N
51	Alaska or Puerto Rico / VI	Strike-slip	WUS	-	D	N
52	Alaska or Puerto Rico / VI	Reverse	WUS	-	D	N
53	Alaska or Puerto Rico / VI	Normal	WUS	-	D	N
54	Alaska or Puerto Rico / VI - Subduction	Interslab	WUS	-	D	N
55	Alaska or Puerto Rico / VI - Subduction	Interface	WUS	-	D	N
56	Hawaii	Reverse	WUS	-	D	N
57	Hawaii - Volcanic/Shallow	Normal	WUS	-	D	N
58	Hawaii - Volcanic/Deep	Normal	WUS	-	D	N
59	Hawaii - Munson and Thurber (1997)	Normal	WUS	R_{JB}	P	N

** See Table 4-5 for distance types.*

*** See definitions of the dependent attenuation relationship combinations in Table 4-4.*

4.1.3.3.1 Combination Attenuation Relationships

Table 4-4 summarizes the 13 combinations of 14 relations used by Hazus to model ground motions, in a manner similar to that developed by the USGS for the 2008 seismic hazard maps. WUS relations, including the NGA ground motions, are used for similar faulting in Alaska, Hawaii, Puerto Rico, and U.S. Virgin Islands in lieu of older relations for these regions.

Since earthquake energy travels more efficiently in the colder and thicker crust of the central and eastern U.S., the combination CEUS attenuation function predicts significantly stronger ground shaking than the combinations of WUS attenuation functions for the same scenario earthquake (e.g., same moment magnitude, soil type, and distance to source).

Table 4-4 Combination Attenuation Relationships

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

[1] CEUS = (O.25) Toro et al. 97 + (0.125) Frankel et al. 96 + (0.125) Campbell 03 + (0.25) AB 06 + (0.125) TP 05 + (0.125) Silva et al. 02
[2] NMSZ = (0.2) Toro 97+ (0.1) Frankel 96 + (0.1) Campbell 03 + (0.2) AB 06 + (0.1) TP 05 + (0.1) Silva et al. 02 + (0.2) Somerville et al. 01
[3] WUS - Strike-Slip (Vertical or Foot Wall) – NGA Mix = (0.33) BA 2008 + (0.33) CB 2008 + (0.33) CY 2008
[4] WUS - Strike Slip (Hanging Wall) – NGA Mix = (0.33) BA 2008 + (0.33) CB 2008 + (0.33) CY 2008
[5] WUS - Reverse (Hanging Wall) – NGA Mix = (0.33) BA 2008 + (0.33) CB 2008 + (0.33) CY 2008
[6] WUS - Reverse (Foot Wall) – NGA Mix = (0.33) BA 2008 + (0.33) CB 2008 + (0.33) CY 2008
[7] WUS - Normal (Hanging Wall) – NGA Mix = (0.33) BA 2008 + (0.33) CB 2008 + (0.33) CY 2008
[8] WUS – Normal (Foot Wall) – NGA Mix = (0.33) BA 2008 + (0.33) CB 2008 + (0.33) CY 2008
[9] Cascadia Subduction Zone - Plate Interface (IT) = (0.25) Youngs et al. 1997 + (0.25) AB 2003, global + (0.5) Zhao et al. 2006
[10] Cascadia Subduction Zone – Intraslab = (0.25) Youngs et al. 1997 + AB Global 2003 + (0.5) Zhao et al. 2006
[11] Megathrust/Interface = (0.5) Sadigh et al. 97 + (0.5) Youngs et al. 97 (IT) Note. PR-VI = (0.1) Youngs et. Al 97 at R>58 km.
[12] Deep/Deeper Intraslab = (0.5) Youngs et al. 1997 + (0.5) AB Global 2003. Note. At least two different fault depths.
[13] Shallow (non-CEUS) Unknown Faults = NGA Mix assuming (0.5) SS + (0.25) RV-FW + (0.25) RV-HW fault type

4.1.3.4 Source-to-Site Distance Measures for Attenuation Functions

The source-to-site distance is an integral part of each attenuation relationship and characterizes the decrease in ground shaking intensity as the distance from the earthquake source increases. Table 4-5 describes the distance measures used in the Methodology.

Table 4-5 Source-to-Site Distance Measures

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

Figure 4-3 illustrates the distance measures from a vertical fault plane while Figure 4-4 illustrates the same measure for a dipping fault. In the Methodology, all distances and fault dimensions are in kilometers.

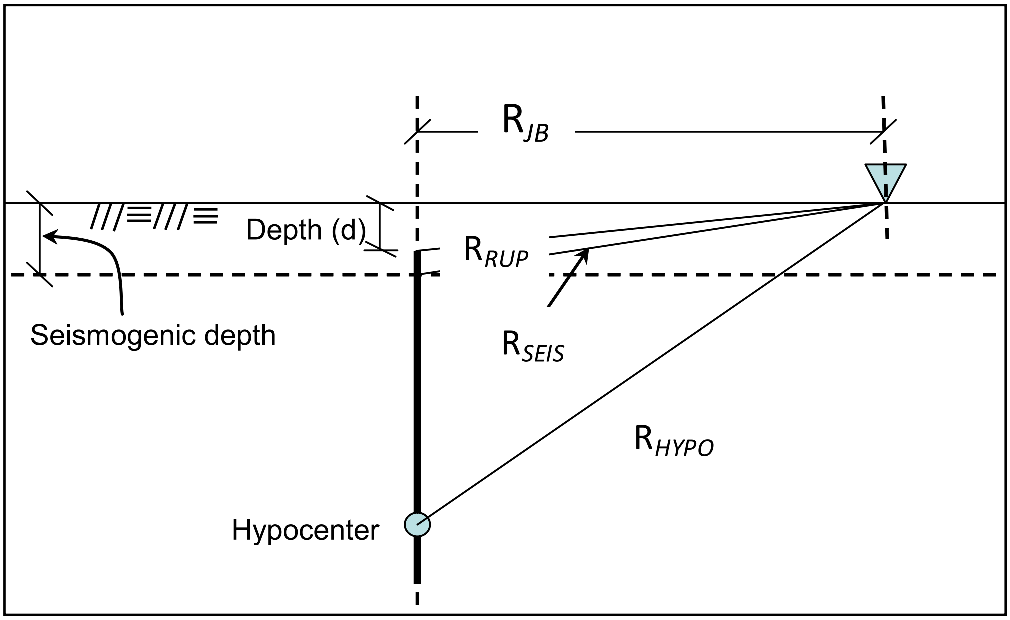


Figure 4-3 Source-to-Site Distances for Vertical Faults

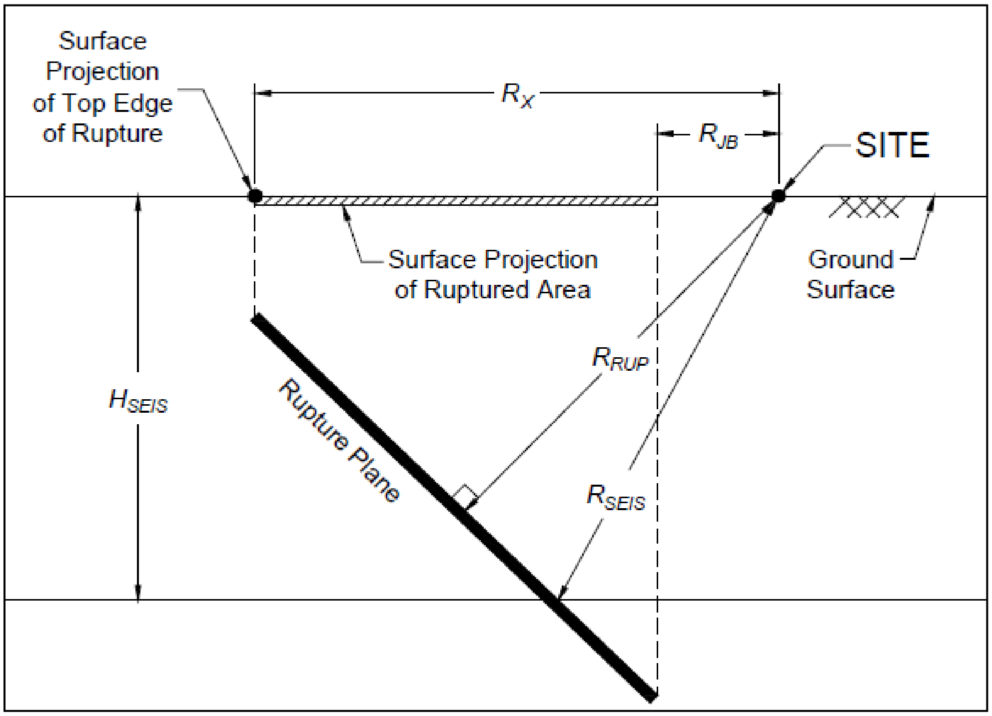


Figure 4-4 Source-to-Site Distances for Dipping Faults

4.1.3.5 Amplification of Ground Shaking – Local Site Conditions

Amplification of ground shaking to account for local site conditions is based on the site classes, and soil amplification factors proposed for the 1994 and 1997 NEHRP Provisions (FEMA, 1995; FEMA, 1997), and subsequent updates conducted at the Pacific Earthquake Engineering Research Center (Stewart and Seyhan, 2013). The NEHRP Provisions define a standardized site geology classification scheme and specify soil amplification factors for most site classes. The classification scheme of the NEHRP Provisions is based, in part, on the average shear wave velocity of the upper 30 meters of the local site geology (Vs30), as shown in Table 4-6. Geotechnical experts may be required to relate the soil classification scheme of local soil maps to the classification scheme shown in Table 4-6.

Table 4-6 Site Classes

Site Class	Site Class Description	Shear Wave Velocity (m/sec)	
		Minimum	Maximum
A	**HARD ROCK:** Eastern United States sites only	1,500	
B	**ROCK**	760	1,500
C	**VERY DENSE SOIL AND SOFT ROCK:** Untrained shear strength $u_s \geqq$ 2000 psf ($u_s \geqq$ 100 kPa) or N $\geqq$ 50 blows/ft	360	760
D	**STIFF SOILS:** Stiff soil with undrained shear strength 1000 psf $\leqq u_s \leqq$ 2000 psf (50 kPa $\leqq u_s \leqq$ 100 kPa) or 15 $\leqq$ N $\leqq$ 50 blows/ft	180	360
E	**SOFT SOILS:** Profile with more than 10 ft (3 m) of soft clay defined as soil with plasticity index PI > 20, moisture content *w* > 40% and undrained shear strength u_s < 1,000 psf (50 kPa) (N < 15 blows/ft)		180

Site Class	Site Class Description	Shear Wave Velocity (m/sec)	
		Minimum	Maximum
F	**SOILS REQUIRING SITE SPECIFIC EVALUATIONS:** • **Soils vulnerable to potential failure or collapse under seismic loading** (e.g., liquefiable soils, quick and highly sensitive clays, collapsible weakly cemented soils.) • **Peats and/or highly organic clays** (10 ft (3 m) or thicker layer) • **Very high plasticity clays** (25 ft (8 m) or thicker layer with plasticity index >75) • **Very thick soft/medium stiff clays** (120 ft (36 m) or thicker layer)		

** Site Classes are based on 1997 NEHRP Provisions*

Soil amplification factors are provided in Table 4-7 for Site Classes A, B, C, D, and E. No amplification factors are available for Site Class F, which requires special site-specific geotechnical evaluation and is not used in the Methodology. The original NEHRP amplification factors used in Hazus were updated as of Hazus 2.2 in 2015 to reflect recent research (Stewart and Seyhan, 2013). These updated amplification factors generally increased the amount of amplification in softer soils at lower levels of ground motions and included slight decreases at bedrock sites or at higher levels of ground motions.

Table 4-7 Site Amplification Factors

Spectral Acceleration	Site Class				
	A	B	C	D	E
Short-Period, S_{AS} (g)	**Short-Period Amplification Factor, F_A**				
< 0.25	0.8	0.9	1.3	1.6	2.4
0.50	0.8	0.9	1.3	1.4	1.7
0.75	0.8	0.9	1.2	1.2	1.3
1.0	0.8	0.9	1.2	1.1	1.1
1.25	0.8	0.9	1.2	1.0	0.9
> 1.5	0.8	0.9	1.2	1.0	0.8
1-Second Period, S_{A1} (g)	**Mid-Period Amplification Factor, F_V**				
< 0.1	0.8	0.8	1.5	2.4	4.2
0.2	0.8	0.8	1.5	2.2	3.3
0.3	0.8	0.8	1.5	2.0	2.8
0.4	0.8	0.8	1.5	1.9	2.4
0.5	0.8	0.8	1.5	1.8	2.2
> 0.6	0.8	0.8	1.4	1.7	2.0
Peak Ground Acceleration (g)	**Peak Ground Acceleration Amplification Factor, F_{PGA}**				
< 0.1	0.8	0.9	1.3	1.6	2.4
0.2	0.8	0.9	1.2	1.4	1.9
0.3	0.8	0.9	1.2	1.3	1.6
0.4	0.8	0.9	1.2	1.2	1.4
0.5	0.8	0.9	1.2	1.1	1.2
> 0.6	0.8	0.9	1.2	1.1	1.1

** Source: Stewart and Seyhan, 2013*

Neither the original NEHRP Provisions nor the 2013 updates include soil amplification factors for PGV. The Methodology amplifies rock (Site Class B) PGV by the same factor as the original NEHRP amplification factors for 1.0-second spectral acceleration, given in Table 4-8.

Table 4-8 Site Amplification Factors for PGV*

Peak Ground Velocity (in/sec)	Site Class				
	A	B	C	D	E
< 3.75	0.8	1.0	1.7	2.4	3.5
7.5	0.8	1.0	1.6	2.0	3.2
11.25	0.8	1.0	1.5	1.8	2.8
15.0	0.8	1.0	1.4	1.6	2.4
18.75	0.8	1.0	1.3	1.5	2.4

** Based on 1997 NEHRP Amplification Factors for 1.0 Second Period, FV*

4.1.3.5.1 Construction of Demand Spectra

Demand spectra including soil amplification effects are constructed at short-periods using Equation 4-6 and at long-periods using Equation 4-7. The period, T_{AV}, which defines the transition period from constant spectral acceleration to constant spectral velocity is a function of site class, as given in Equation 4-8. The period, T_{VD}, which defines the transition period from constant spectral velocity to constant spectral displacement is defined earlier in Equation 4-4, and is not a function of site class.

Equation 4-6

$$S_{ASi} = S_{AS} * F_{Ai}$$

Equation 4-7

$$S_{A1i} = S_{A1} * F_{Vi}$$

Equation 4-8

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

Where:

S_{ASi}	is short-period spectral acceleration for Site Class i (in units of g)
S_{AS}	is short-period spectral acceleration for Site Class B (in units of g)
F_{Ai}	is the short-period amplification factor for Site Class i, as specified in Table 4-7 for spectral acceleration, S_{AS}
S_{A1i}	is 1-second period spectral acceleration for Site Class i (in units of g)
S_{A1}	is 1-second period spectral acceleration for Site Class B (in units of g)
F_{Vi}	is the 1-second period amplification factor for Site Class i, as specified in Table 4-7for spectral acceleration, S_{A1}
T_{AVi}	is the transition period between constant spectral acceleration and constant spectral velocity for Site Class i (seconds).

Figure 4-5 illustrates construction of response spectra for Site Class D (stiff soil) and E (soft soil) from Site Class B (rock) response spectra. These spectra represent response (of a 5%-damped, linear-elastic single-degree-of-freedom system) located at a WUS site, 20 km from a magnitude **M** = 7.0 earthquake, as predicted by the default combination of WUS attenuation relationships, shows the significance of soil type on site response (i.e., increase in site response with decrease in shear wave velocity) and the increase in the value of the transition period, T_{AV}, with decrease in shear wave velocity.

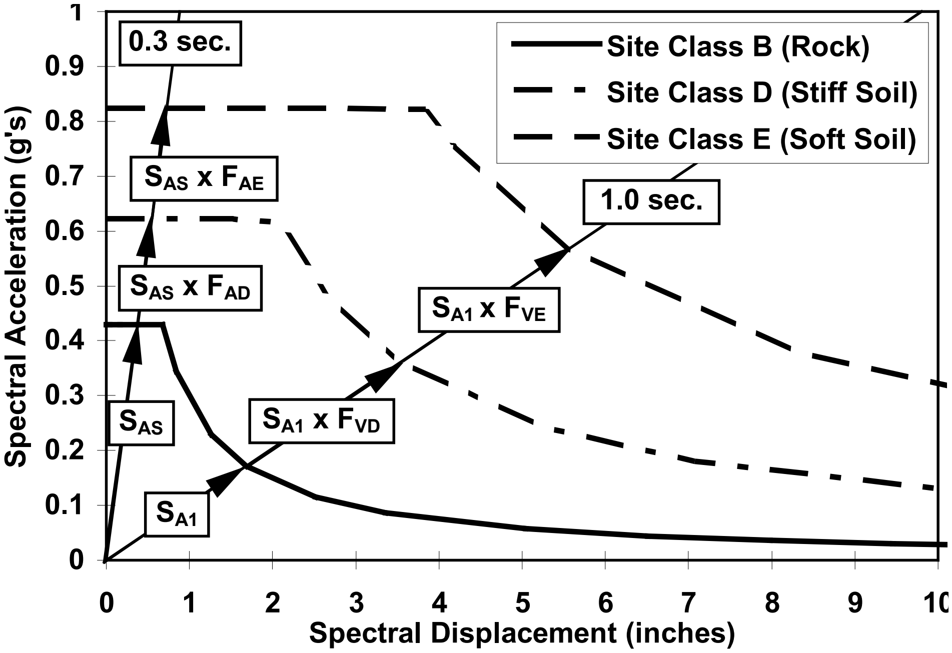


Figure 4-5 Example Construction of Site Class B, C, and D Spectra - WUS

4.1.4 Guidance for Expert-Generated Ground Motion Estimation

Ground motion estimation is a sophisticated combination of earth science, engineering, and probabilistic methods and should not be attempted by users without the proper expertise. For users who do not have the expertise to estimate ground motion and who may need guidance selecting which existing attenuation function to use, Table 4-3 summarizes the 59 choices that currently exist within Hazus. Note that the dependent attenuation functions are the “cocktail”-based functions in Hazus (e.g., they are combinations of other standalone attenuation functions like 25% of A + 45% of B + 30% of C, and so on).

When the user creates a Study Region, Hazus will recognize whether the region is in the CEUS or the WUS (see Figure 4-1), and automatically filter the attenuation functions to show only those functions applicable for that region, including both primary and dependent (“cocktail”-based) attenuation functions. The user may choose different attenuation functions depending on the purpose of their analysis, for example:

- To understand the effects of different attenuation functions on the results. This is particularly important given that ground motion has a significant impact on the results.
- To simulate and set up upper bound and lower bound estimates due to ground motion. In this case, the user needs to know which of the attenuation functions provide the smallest shaking and which of the attenuation functions provide the largest shaking.

- When a user wants to choose a particular attenuation function, they should consider the distance between the source and the community/Study Region for which upper and lower bound losses need to be determined.

4.2 Ground Failure

Three types of ground failure are considered: liquefaction, landslide, and surface fault rupture. Each of these types of ground failure is quantified by permanent ground deformation (PGD). Methods and alternatives for determining PGD due to each mode of ground failure are discussed below. The evaluation of the hazard includes both assessing the probability of the hazard occurring and estimating the magnitude of the resulting ground displacement.

4.2.1 Input Requirements and Output Information

4.2.1.1 Input

Liquefaction

- A geologic map based on the age, depositional environment, and the material characteristics of the geologic units should be used with Table 4-9 to create a liquefaction susceptibility map.
- Users can input a groundwater depth map, or a default depth of 5 feet may be assumed.
- Earthquake Moment Magnitude (**M**)

Landslide

A geologic map, a topographic map, and a map with groundwater conditions should be used with Table 4-14 to produce a landslide susceptibility map.

- Earthquake Moment Magnitude (**M**)

Surface Fault Rupture

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

4.2.1.2 Output

Liquefaction and Landslide

- A map depicting estimated permanent ground deformations, along with site-specific values of PGD.

Surface Fault Rupture

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

4.2.2 Description of Methods

4.2.2.1 Liquefaction

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

Youd and Perkins (1978) have addressed the liquefaction susceptibility of various types of soil deposits by assigning a qualitative susceptibility rating based on general depositional environment and geologic age of the deposit. The relative susceptibility ratings of Youd and Perkins (1978) shown in Table 4-9 indicate that recently deposited, relatively unconsolidated soils such as Holocene-age river channel, floodplain, and delta deposits, and uncompacted artificial fills located below the groundwater table have high to very high liquefaction susceptibility. Sands and silty sands are particularly susceptible to liquefaction. Silts and gravels also are susceptible to liquefaction, and some sensitive clays have exhibited liquefaction-type strength losses (Updike et al., 1988).

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

4.2.2.1.1 Liquefaction Susceptibility

The initial step of the liquefaction hazard evaluation is to characterize the relative liquefaction susceptibility of the soil/geologic conditions of a region or subregion. Susceptibility is characterized by utilizing geologic map information and the classification system presented by Youd and Perkins (1978) as summarized in Table 4-9. Large-scale (e.g., 1:24,000 or greater) or smaller-scale (e.g., 1:250,000) geologic maps are generally available for many areas from geologists at regional USGS offices, state geological agencies, or local government agencies. The geologic maps typically identify the age, depositional environment, and material type for a particular mapped geologic unit. Based on these characteristics, a relative liquefaction susceptibility rating (e.g., very low to very high) is assigned from Table 4-9. Mapped areas of geologic materials characterized as rock or rock-like are considered for the analysis to represent no liquefaction hazard.

Liquefaction susceptibility maps produced for certain regions [e.g., greater San Francisco region (Knudsen et al., 2000; Witter et al., 2006); San Diego (Power et al., 1982); Los Angeles (Tinsley et al., 1985); San Jose (Power et al., 1991); Seattle (Grant et al., 1991); CEUS (CUSEC State Geologists, 2008), among others] are also available and may be utilized in the hazard analysis. On-line map portals are also available in some areas, such as from the Oregon Department of Geology and Mineral Industries and the Washington Department of Natural Resources.

Table 4-9 Liquefaction Susceptibility of Sedimentary Deposits

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

** After Youd and Perkins, 1978*

4.2.2.1.2 Probability of Liquefaction

The likelihood of experiencing liquefaction at a specific location is primarily influenced by the susceptibility of the soil, the amplitude and duration of ground shaking, and the depth of groundwater. The relative susceptibility of soils within a particular geologic unit is assigned as previously discussed. It is recognized that, in reality, natural geologic deposits as well as man-placed fills encompass a range of liquefaction susceptibilities due to variations of soil type (i.e., grain size distribution), relative density, etc. Therefore, portions of a geologic map unit may not be susceptible to liquefaction, and this should be considered in assessing the probability of liquefaction at any given location within the unit. In general, it is expected that non-susceptible portions will be smaller for higher susceptibilities. This "reality" is incorporated by a probability factor that quantifies the proportion of a geologic map unit deemed susceptible to liquefaction (i.e., the likelihood of susceptible conditions existing at any given location within the unit). For the various susceptibility categories, suggested default values are provided in Table 4-10.

Table 4-10 Proportion of Map Unit Susceptible to Liquefaction

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

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

As previously stated, the likelihood of liquefaction is significantly influenced by ground shaking amplitude (i.e., peak acceleration, PGA), ground shaking duration as reflected by earthquake magnitude, **M**, and groundwater depth. Thus, the probability of liquefaction for a given susceptibility category can be determined by Equation 4-9.

Equation 4-9

$$\mathrm{P}[\mathrm{Liquefaction}_{SC}] = \frac{\mathrm{P}[\mathrm{Liquefaction}_{SC}\,|\mathrm{PGA} = \mathrm{a}]}{\mathrm{K_M} * \mathrm{K_W}} * \mathrm{P_{ml}}$$

Where:

$\mathrm{P}[\mathrm{Liquefaction}_{SC}\,|\mathrm{PGA} = \mathrm{a}]$	is the conditional liquefaction probability for a given susceptibility category at a specified level of peak ground acceleration (Figure 4-6)
K_M	is the moment magnitude (**M**) correction factor (Equation 4-10)
K_w	is the groundwater correction factor (Equation 4-11)
P_{ml}	proportion of map unit susceptible to liquefaction (Table 4-10)

Relationships between liquefaction probability and peak ground acceleration (PGA) are defined for the given susceptibility categories in Table 4-11 and also represented graphically in Figure 4-6. These relationships have been defined based on state-of-practice empirical procedures, as well as the statistical modeling of the empirical liquefaction catalog presented by Liao et al. (1988) for representative penetration resistance characteristics of soils within each susceptibility category as gleaned from regional liquefaction studies cited previously. Note that the relationships given in Figure 4-6 are simplified representations of the relationships that would be obtained using Liao et al. (1988) or empirical procedures.

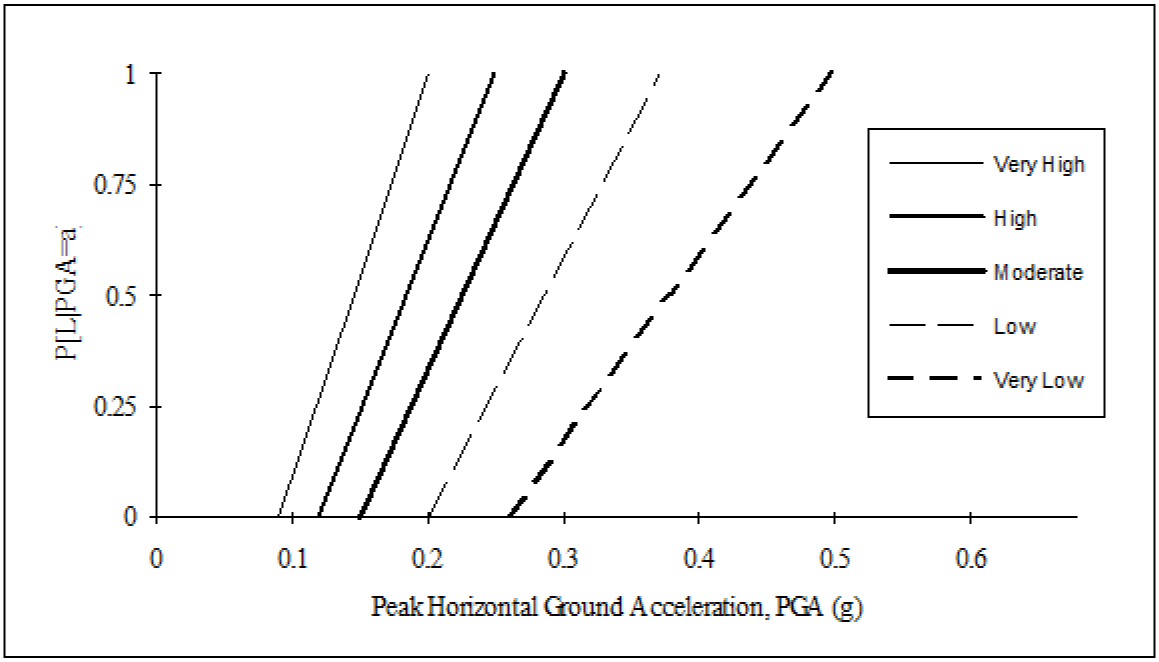


Figure 4-6 Conditional Liquefaction Probability Relationships for Liquefaction Susceptibility Categories

Table 4-11 Conditional Probability Relationship for Liquefaction Susceptibility Categories

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

The conditional liquefaction probability relationships presented in Figure 4-6 were developed for a **M** =7.5 earthquake and an assumed groundwater depth of five feet. Correction factors to account for other moment magnitudes (**M**) and groundwater depths are given by Equation 4-10 and Equation 4-11 respectively. These modification factors are well recognized and have been explicitly incorporated in state-of-practice empirical procedures for evaluating the liquefaction potential (Seed and Idriss, 1982; Seed et al., 1985; National Research Council, 1985). These relationships are also presented graphically in Figure 4-7 and Figure 4-8. The magnitude and groundwater depth corrections are made automatically in the methodology. The modification factors can be computed using the relationships shown in Equation 4-10 and Equation 4-11:

Equation 4-10

$$K_M = 0.0027\mathbf{M}^3 - 0.0267\mathbf{M}^2 - 0.2055\mathbf{M} + 2.9188$$

Equation 4-11

$$K_w = 0.022d_w + 0.93$$

Where:

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

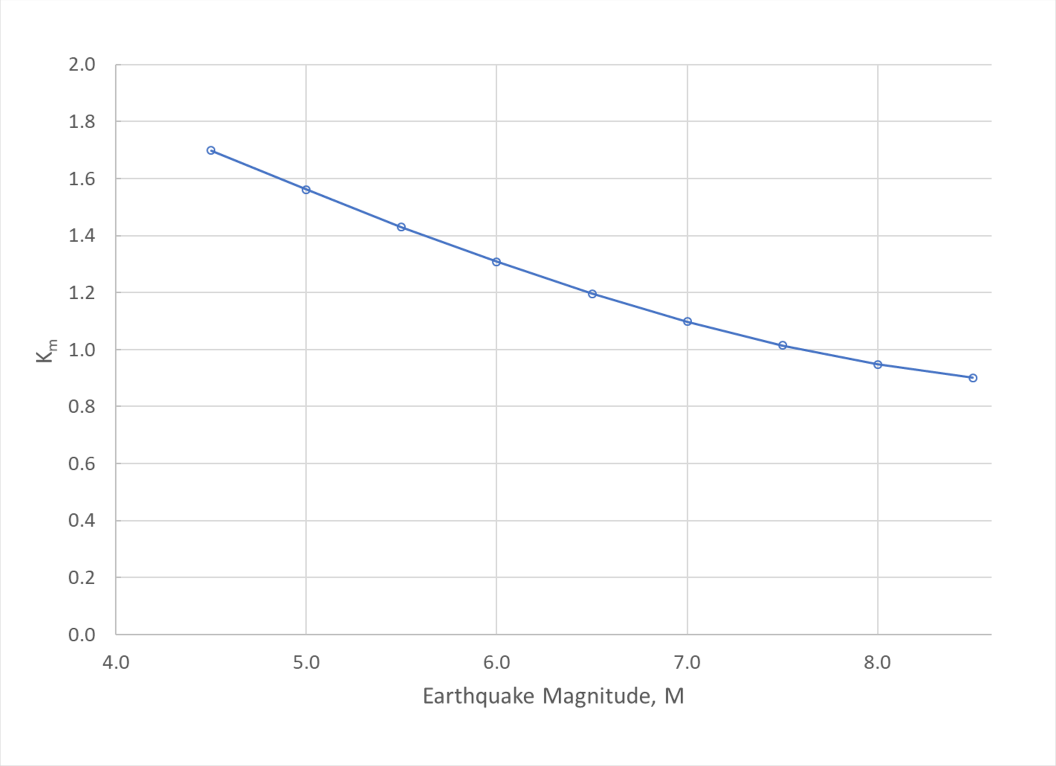


Figure 4-7 Moment Magnitude (M) Correction Factor for Liquefaction Probability Relationships

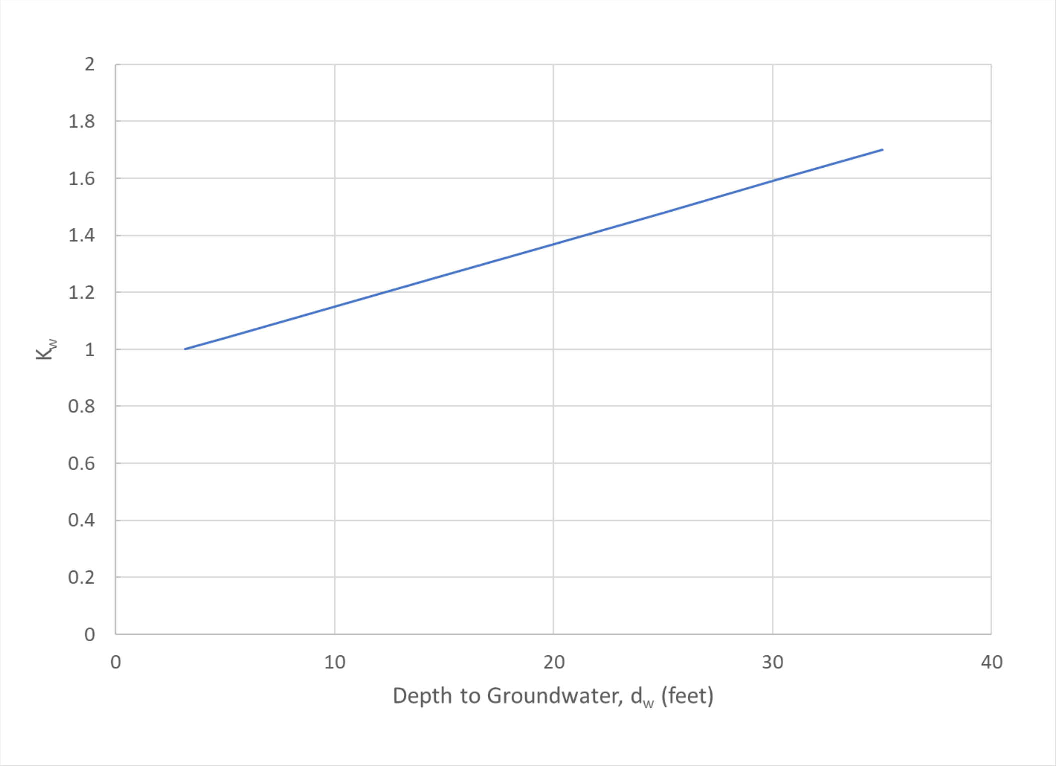


Figure 4-8 Groundwater Depth Correction Factor for Liquefaction Probability Relationships

4.2.2.1.3 Permanent Ground Displacements due to Liquefaction

4.2.2.1.3.1 Lateral Spreading

The expected permanent ground displacements due to lateral spreading for a given susceptibility category can be determined using the relationship shown in Equation 4-12:

Equation 4-12

$$\mathrm{E}[\mathrm{PGD}_{\mathrm{SC}}] = \mathrm{K}_{\Delta} * \mathrm{E}[\mathrm{PGD}|(\mathrm{PGA}/\mathrm{PL}_{\mathrm{SC}}) = \mathrm{a}]$$

Where:

$\mathrm{E}[\mathrm{PGD}\|(\mathrm{PGA}/\mathrm{PL}_{\mathrm{SC}}) = \mathrm{a}]$	is the expected permanent ground displacement for a given susceptibility category under a specified level of normalized ground shaking (PGA/PGA(t)) (Figure 4-9)
PGA(t)	is the threshold ground acceleration necessary to induce liquefaction (Table 4-12)
K_{Δ}	is the displacement correction factor given by Equation 4-13.

This relationship for lateral spreading was developed by combining the Liquefaction Severity Index (LSI) relationship presented by Youd and Perkins (1987) with the ground motion attenuation relationship developed by Sadigh et al. (1986) as presented in Joyner and Boore (1988). The ground shaking level in Figure 4-9 has been normalized by the threshold peak ground acceleration PGA(t) corresponding to zero probability of liquefaction for each susceptibility category as shown on Figure 4-9. The PGA(t) values for different susceptibility categories are summarized in Table 4-12.

The displacement term in Equation 4-12 is based on **M** = 7.5 earthquakes. Displacements for other magnitudes are determined by modifying this displacement term by the displacement correction factor given by Equation 4-13. This equation is based on work done by Seed and Idriss (1982). The displacement correction factor, K_Δ, is shown graphically in Figure 4-10.

Equation 4-13

$$K_\Delta = 0.0086\mathbf{M}^3 - 0.0914\mathbf{M}^2 + 0.4698\mathbf{M} - 0.9835$$

Where:

M is moment magnitude

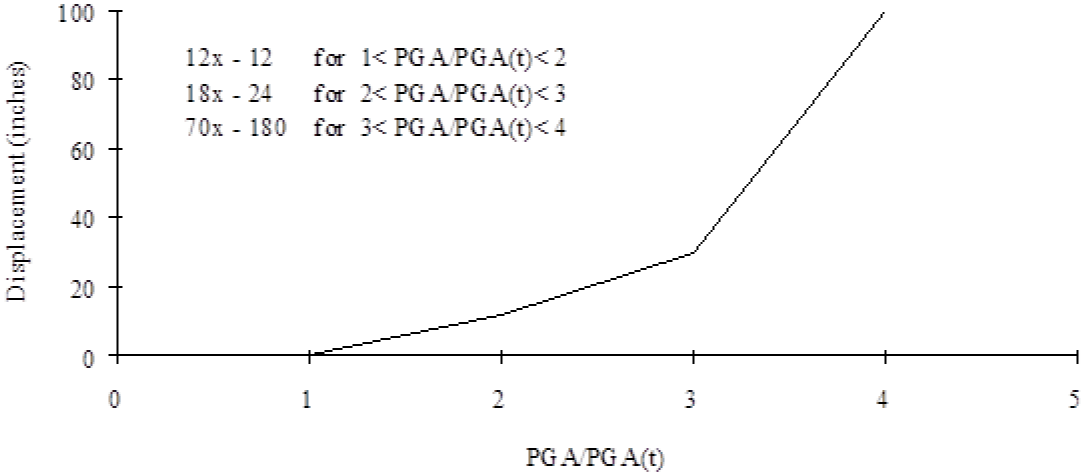


Figure 4-9 Lateral Spreading Displacement Relationship

Table 4-12 Threshold Ground Acceleration (PGA(t)) Corresponding to Zero Probability of Liquefaction

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

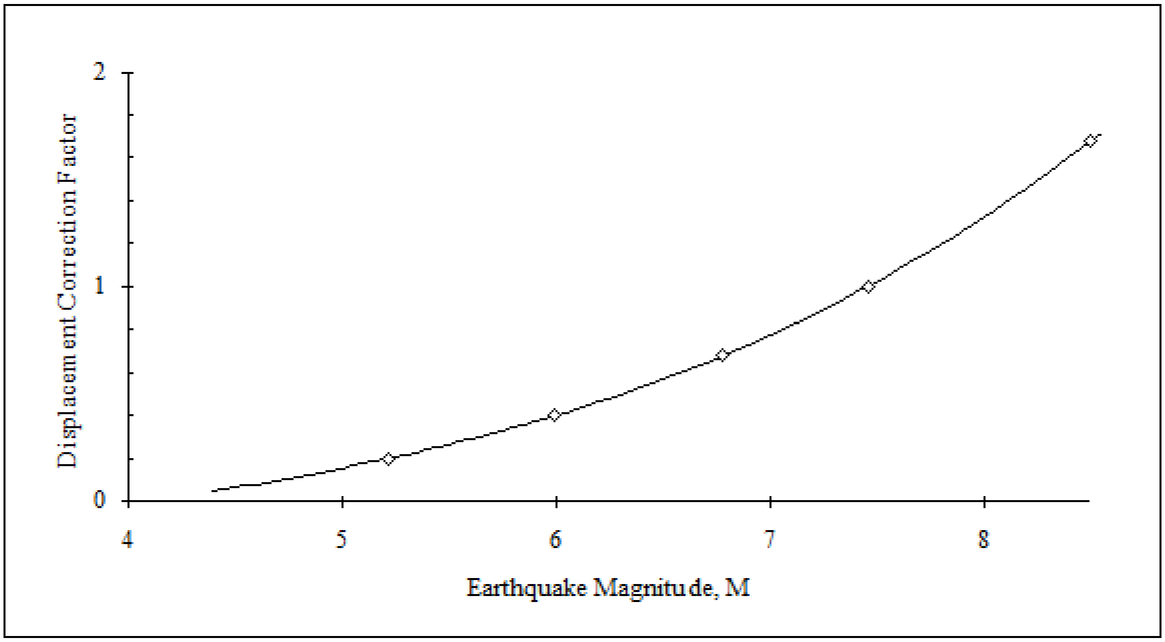


Figure 4-10 Displacement Correction Factor K_Δ for Lateral Spreading Displacement Relationships

4.2.2.1.3.2 Ground Settlement

Ground settlement associated with liquefaction is assumed to be related to the susceptibility category assigned to an area. This assumption is consistent with the relationship presented by Tokimatsu and Seed (1987) that indicate strong correlations between volumetric strain (settlement) and soil relative density (a measure of susceptibility). Additionally, experience has shown that deposits of higher susceptibility tend to have increased thicknesses of potentially liquefiable soils. Based on these considerations, the ground settlement amplitudes are given in Table 4-13 for the portion of a soil deposit estimated to experience liquefaction at a given ground motion level. The uncertainty associated with these settlement values is assumed to have a uniform probability distribution within bounds of one-half to two times the respective value. It is noted that the relationship presented by Tokimatsu and Seed (1987) demonstrate very little dependence of settlement on ground motion level given the occurrence of liquefaction. The expected settlement at a location, therefore, is the product of the probability of liquefaction (Equation 4-9) for a given ground motion level and the characteristic settlement amplitude appropriate to the susceptibility category (Table 4-13).

Table 4-13 Ground Settlement Amplitudes for Liquefaction Susceptibility Categories

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

4.2.2.2 Landslide

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

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

4.2.2.2.1 Landslide Susceptibility

The landslide hazard evaluation requires the characterization of the landslide susceptibility of the soil/geologic conditions of a region or subregion. Susceptibility is characterized by the geologic group, slope angle, and critical acceleration. The acceleration required to initiate slope movement is a complex function of slope geology, steepness, groundwater conditions, type of landslide, and history of previous slope performance. At the present time, a generally accepted relationship or simplified methodology for estimating a_c has not been developed.

The relationship proposed by Wilson and Keefer (1985) is utilized in the Methodology. This relationship is shown in Figure 4-11. Landslide susceptibility is measured on a scale of I to X, with I being the least susceptible. The site condition is identified using three geologic groups (strongly cemented rocks, weakly cemented rocks and soils, and argillaceous rocks, or rocks and soils consisting of or containing clay) and groundwater level. The full description for each geologic group and its associated susceptibility is given in Table 4-14. The groundwater condition is categorized as either dry condition (groundwater below the level of the slide) or wet condition (groundwater level at ground surface). The critical acceleration is then estimated for the respective geologic and groundwater conditions and the slope angle. To avoid calculating the occurrence of landslide for very low or zero slope angles and critical accelerations, lower bounds for slope angles and critical accelerations are established. These bounds are shown in Table 4-15. Figure 4-11 shows the Wilson and Keefer relationships within these bounds.

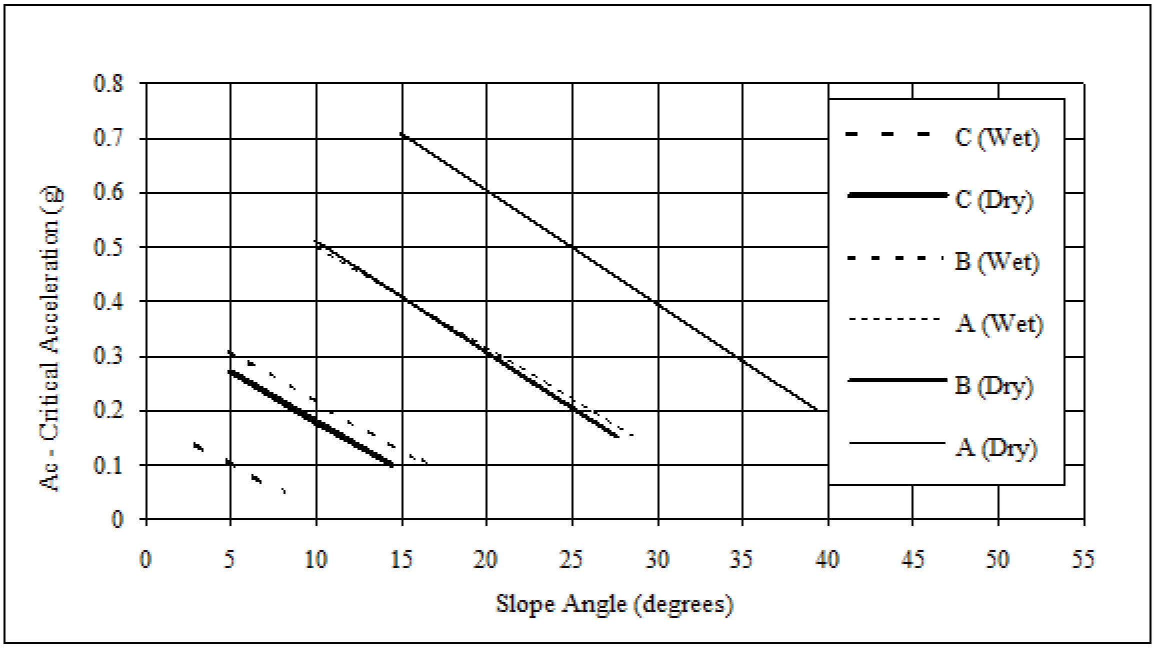


Figure 4-11 Critical Acceleration as a Function of Geologic Group and Slope Angle

Table 4-14 Landslide Susceptibility of Geologic Groups

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

Table 4-15 Lower Bounds for Slope Angles and Critical Accelerations for Landslide Susceptibility

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

As pointed out by Wieczorek et al. (1985), the relationships in Figure 4-11 are conservative, representing the most landslide-susceptible geologic types likely to be found in the geologic group. Thus, in using this relationship, further consideration must be given to evaluating the probability of slope failure.

In Table 4-16, landslide susceptibility categories are defined as a function of critical acceleration. Then, using Wilson and Keefer's relationship in Figure 4-11 the lower bound values in Table 4-15, the susceptibility categories are assigned as a function of the geologic group, groundwater conditions, and slope angle in Table 4-14. Table 4-14 and Table 4-16 thus define the landslide susceptibility.

Table 4-16 Critical Accelerations (a_c) for Susceptibility Categories

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

4.2.2.2.2 Probability of Having a Landslide Susceptible Deposit

Because of the conservative nature of the Wilson and Keefer (1985) correlation, an assessment is made of the percentage of a landslide susceptibility category that is expected to be susceptible to landslide. Based on Wieczorek et al. (1985), this percentage is selected from Table 4-17 as a function of the susceptibility categories. Thus, at any given location, there is a specified probability of having a landslide-susceptible deposit, and a landslide either occurs or does not occur within susceptible deposits, depending on whether the induced peak ground acceleration ais exceeds the critical acceleration a_c.

Table 4-17 Percentage of Map Area Having a Landslide-Susceptible Deposit

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

4.2.2.2.3 Permanent Ground Displacements due to Landslide

The expected permanent ground displacements due to landslide are determined using Equation 4-14 below.

Equation 4-14

$$E[PGD] = E[d/a_{is}] * a_{is} * n$$

Where:

$E[d/a_{is}]$ is the expected displacement factor (Figure 4-13)

a_{is} is the induced acceleration (in decimal fraction of g's)

n is the number of cycles (Equation 4-15).

A relationship between number of cycles and earthquake moment magnitude (M), based on Seed and Idriss (1982), is shown in Figure 4-12 and can be expressed as given in Equation 4-15.

Equation 4-15

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

The induced peak ground acceleration within the slide mass, a_{is}, represents the average peak acceleration within the entire slide mass. For relatively shallow and laterally small slides, ais is not significantly different than the induced peak ground surface acceleration a_i. For deep and large slide masses, a_{is} less than a_i. For many applications ais may be assumed equal to the accelerations predicted by the peak ground acceleration attenuation relationships being used for the loss estimation study. Considering that topographic amplification of ground motion may also occur on hillside slopes (which is not explicitly incorporated in the attenuation relationships), the assumption of ais equal to ai may be prudent; the default value of the ratio a_{is}/a_i is assumed in the Methodology to be 1.0.

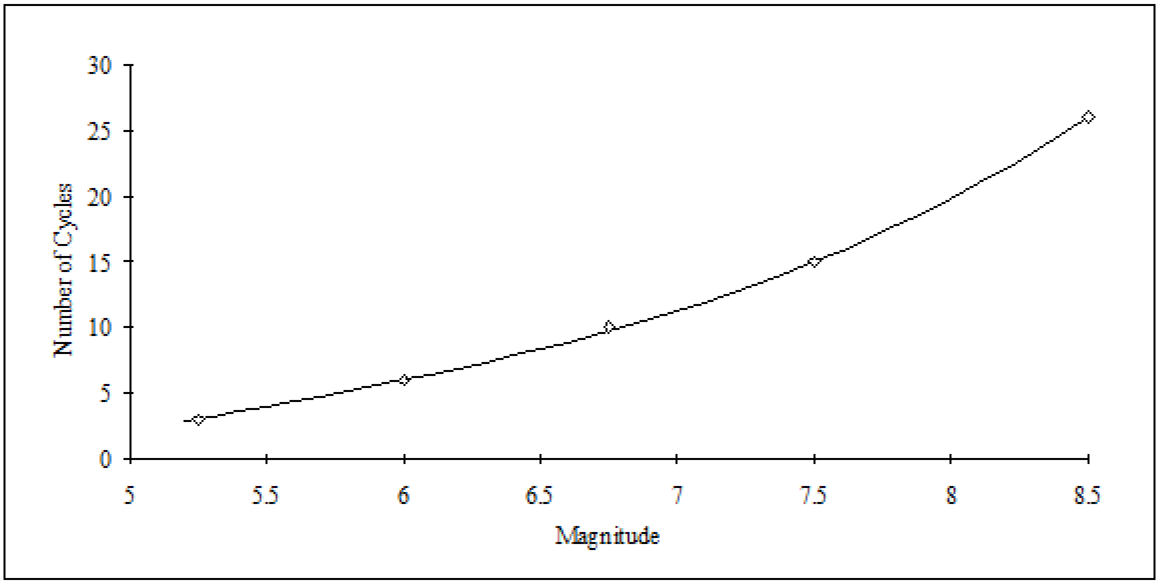


Figure 4-12 Relationship between Earthquake Moment Magnitude and Number of Cycles

A relationship derived from the results of Makdisi and Seed (1978) is used to calculate downslope displacements. In this relationship, shown in Figure 4-13, the displacement factor d/a_{is} is calculated as a function of the ratio a_c/a_{is}. For the relationship shown in Figure 4-13, the range in estimated displacement factor is shown and it is assumed that there is a uniform probability distribution of displacement factors between the upper and lower bounds.

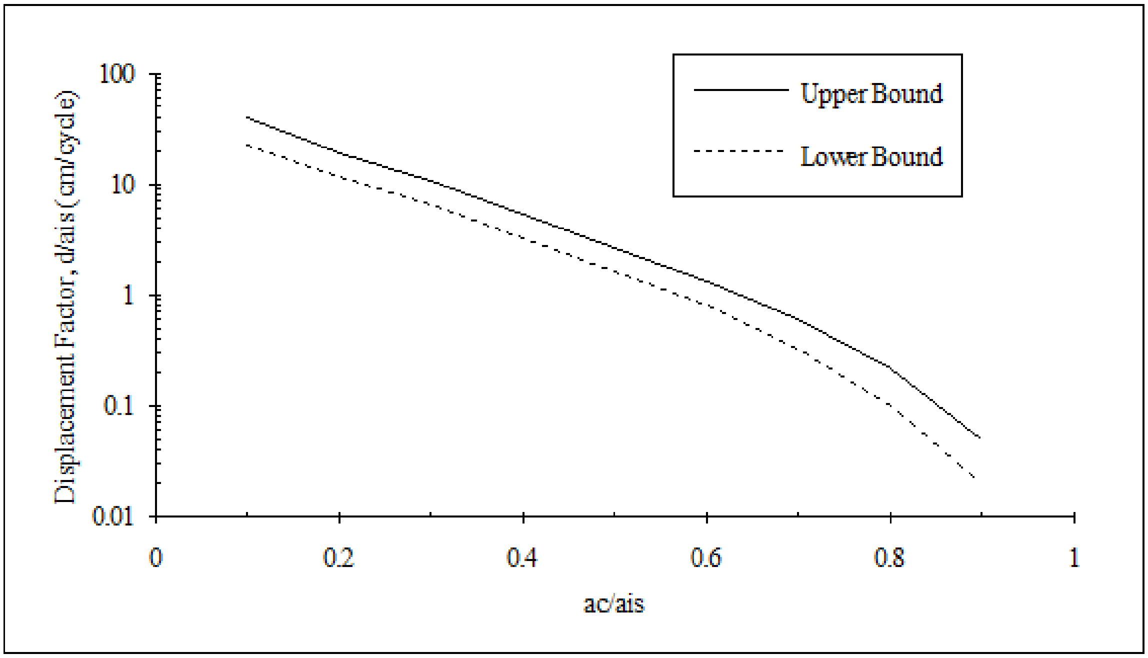


Figure 4-13 Relationship between Displacement Factor and Ratio of Critical Acceleration and Induced Acceleration

4.2.2.3 Surface Fault Rupture

The Methodology uses the correlation between surface fault displacement and earthquake moment magnitude (**M**) developed by Wells and Coppersmith (1994) to estimate fault rupture displacements. The maximum displacement is given by the relationship shown in Figure 4-14. It is assumed that the maximum displacement can potentially occur at any location along the fault, although at the ends of the fault, displacements must drop to zero. The relationship developed by Wells and Coppersmith (1994) is based on their empirical data set for all types of faulting (strike slip, reverse, and normal). It is considered that this relationship provides reasonable estimates for any type of faulting for general loss estimation purposes.

The median maximum displacement (MD) is given by Equation 4-16:

Equation 4-16

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

Where:

M is the moment magnitude.

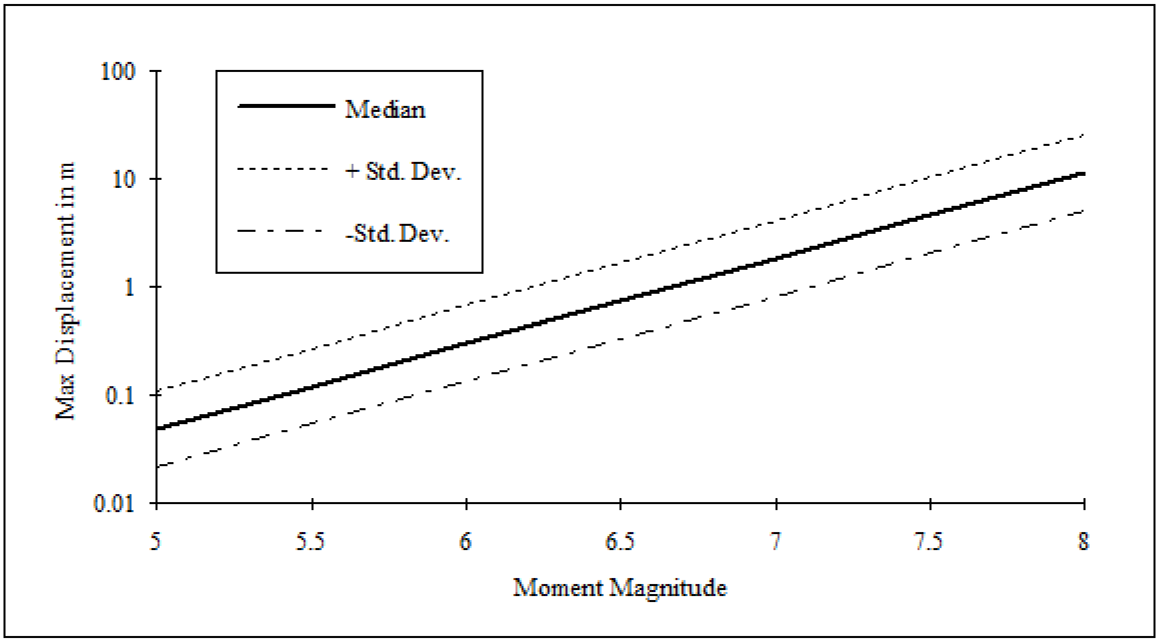


Figure 4-14 Relationship for Estimating Maximum Surface Fault Displacement

Researchers have observed that displacements along a fault vary considerably in amplitude from zero to the maximum value. Wells and Coppersmith (1994) found that the average displacement along the fault rupture segment was approximately equal to one-half the maximum displacement. This is equivalent to a uniform probability distribution for values of displacement ranging from zero to the maximum displacement. As a conservative estimate, a uniform probability distribution from one-half of the maximum fault displacement to the maximum fault displacement could be incorporated for any location along the fault rupture.

4.2.3 Guidance for Expert-Generated Ground Failure Estimation

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

4.2.3.1 Expert Input Requirements

4.2.3.1.1 Liquefaction Input

- A map delineating areas of equal susceptibility (i.e., similar age, deposition, material properties, and groundwater depth). For additional information on preparing liquefaction susceptibility and other hazard maps, see the Hazus Earthquake Model User Guidance, and the Hazus Earthquake Model: FEMA Standard Operating Procedure for Hazus Earthquake Data Preparation and Scenario Analysis (FEMA, 2019).
- Probability distribution of susceptibility variation within each area.
- Relationships between liquefaction probability and ground acceleration for each susceptible area.
- Maps delineating topographic conditions (i.e., slope gradients and/or free-face locations) and susceptible unit thicknesses.

- Relationships between ground displacements (i.e., lateral spreading and settlement) and ground acceleration for each susceptible unit, including probability distribution for displacement; they may vary within a given susceptible unit depending on topographic and liquefied zone thickness conditions.

4.2.3.1.2 Landslide Input

- A map depicting areas of equal critical or yield acceleration a_c (i.e., the values of peak ground acceleration within the slide mass required to initiate landsliding, that is, reduce the factor of safety to 1.0 at the instant of time a_c occurs).
- The probability distribution for a_c within each area.
- The ratio between induced peak ground surface acceleration, ai, and the peak ground acceleration within the slide mass a_{is} (note: could be a constant ratio or could vary for different areas). The value $a_{is}/a_i \leq 1$. The default ratio is 1.0.
- Relationships between landslide displacement d, induced acceleration a_{ic}, and initial or yield acceleration a_c, including the probability distribution for d. Different relationships can be specified for different areas. The default relationship between the displacement factor d/a_{is} and a_c/a_{is} is shown in Figure 4-13.

4.2.3.1.3 Surface Fault Rupture Input

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

4.2.3.2 Liquefaction

It is essential that the user understands the interrelationship among factors that significantly influence liquefaction and associated ground displacement phenomena when defining analysis inputs.

During earthquake ground shaking, induced cyclic shear creates a tendency in most soils to change volume by rearrangement of the soil-particle structure. In loose soils, this volume change tendency is to compact or densify the soil structure. For soils such as fine sands, silts, and clays, permeability is sufficiently low, which allows undrained conditions to prevail in a manner where very little volume change or no volume change can occur during the ground shaking. To accommodate the volume decrease tendency, the soil responds by an increase in the pore-water pressure and corresponding decreases of intergranular effective stress. The relationship between volume change tendency and pore-water increase is described by Martin et al. (1975). Egan and Sangrey (1978) discuss the relationship among compressibility characteristics, the potential amount of pore-water pressure generation and the subsequent loss of strength in various soil materials. In general, more compressible soils such as plastic silts or clays do not generate excess pore-water pressure as quickly or to as large an extent as less compressible soils such as sands. Therefore, silty and clayey soils tend to be less susceptible than sandy soils to liquefaction-type behaviors. Even within sandy soils, the presence of finer-grained materials affects susceptibility as is reflected in the correlations illustrated in Figure 4-15 prepared by Seed et al. (1985) for use in simplified empirical procedures for evaluating liquefaction potential.

Excess pore-water pressure generation and strength loss potential are also highly dependent on the density of the soil, as may also be inferred from Figure 4-15. Density characteristics of soils in a deposit, notably sandy and silty soils, are reflected in penetration resistance measured (i.e., during drilling and sampling an exploratory boring). Using penetration resistance data to help assess liquefaction hazard due to an earthquake is considered a reasonable engineering approach (Seed and Idriss, 1982; Seed et al., 1985; National Research Council, 1985). Many of the factors affecting penetration resistance affect the liquefaction resistance of sandy and silty soils in a similar way and state-of-practice liquefaction evaluation procedures are based on actual performance of soil deposits during historical earthquakes around the world (e.g., Figure 4-15).

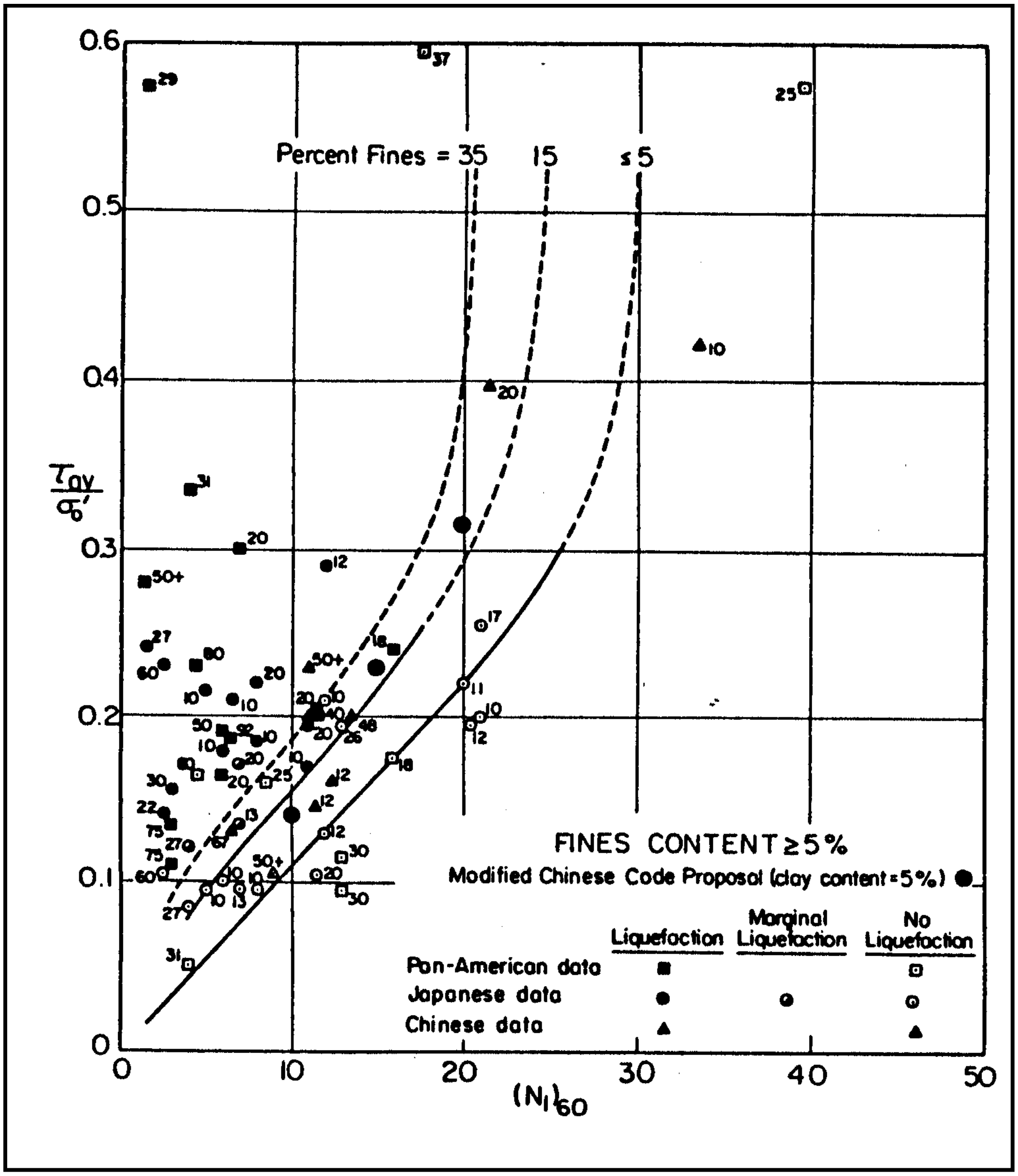


Figure 4-15 Relationship between Cyclic Stress Ratio causing Liquefaction and (N1)60 values (M=7.5)

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

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

These factors have been discussed briefly in the preceding sections. The challenge to the user is to translate regional/local data, experience, and judgment into defining site-specific relationships. The following sections offer additional guidance regarding various components of that process.

4.2.3.2.1 Liquefaction Susceptibility

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

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

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

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

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

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

4.2.3.2.2 Liquefaction Probability

As described previously, simplified procedures for evaluating liquefaction potential presented by Seed et al. (1985), as well as the probabilistic approach presented by Liao et al. (1988) are useful tools for helping to characterize the relationships among liquefaction probability, PGA, duration of shaking (magnitude), groundwater depth, etc. A parameter commonly utilized in these procedures is penetration resistance, which was previously discussed relative to susceptibility. Within a given geologic unit, experience indicates that subsurface investigations may obtain a certain scatter in penetration resistance without necessarily any observable trend for variation horizontally or vertically within that unit. In such cases, a single representative penetration resistance value is often selected for evaluating the liquefaction potential at the site. The representative value is very much site-specific and depends on the particular distribution of penetration resistance values measured. For example, if most of the values are very close to each other, with a few much higher or lower values, the representative value might be selected as the value that is close to the mean of the predominant population of values that are close to each other. On the other hand, if the penetration resistance values appear to be widely scattered over a fairly broad range of values, a value near the 33rd percentile might be more appropriate to select (H.B. Seed, personal communication, 1984). A typical distribution of penetration resistance (N1) for a Holocene alluvial fan deposit (i.e., moderate susceptibility) is shown in Figure 4-16.

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

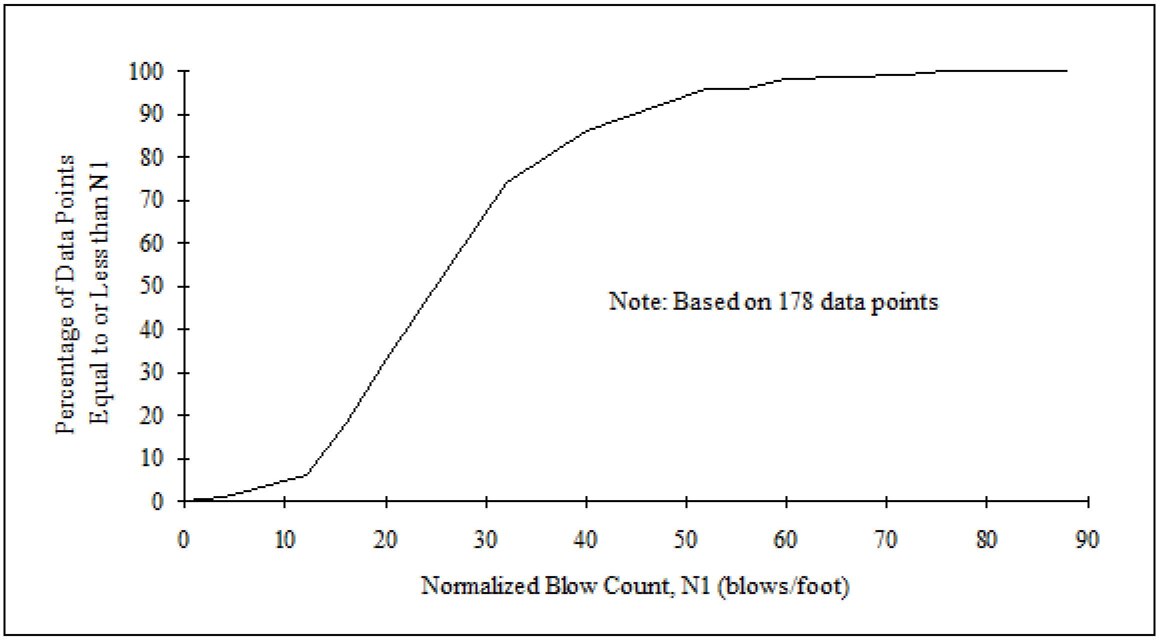


Figure 4-16 Typical Cumulative Distribution Curve of Penetration Resistance for Holocene Alluvial Fan Deposits

4.2.3.2.3 Liquefaction – Permanent Ground Displacement

4.2.3.2.3.1 Lateral Spreading

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

4.2.3.2.3.2 Ground Settlement

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

4.2.3.3 Landslide Susceptibility

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

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

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

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

4.2.3.4 Landslide – Permanent Ground Displacement

In assessing soil deformations using relationships such as shown in Figure 4-13, it should be considered that the relationships are applicable to slope masses that exhibit essentially constant critical accelerations. For cases where significant reduction in strength may occur during the slope deformation process, these relationships may significantly underestimate deformations if the peak strength values are used. For example, deformations cannot be adequately estimated using these simplified correlations in cases of sudden, brittle failure, such as rock falls or soil or rock avalanches on steep slopes.

4.2.3.5 Surface Fault Rupture

Refinements or alternatives that an expert may want to consider in assessing displacements associated with surface fault rupture include: a predictive relationship for maximum fault displacement different from the default relationship (Figure 4-14), specification of regions of the fault rupture (near the ends) where the maximum fault displacement is constrained to lower values, and specification of other than the default relationship for the probability distribution of fault rupture between minimum and maximum values.

Section 5. Direct Physical Damage – General Building Stock

This section describes methods for determining the probability of None, Slight, Moderate, Extensive, and Complete damage to general building stock. General building stock represents typical buildings of a given specific building type designed to either High-Code (HC), Moderate-Code (MC), Low-Code (LC) seismic standards, or not seismically designed (referred to as Pre-Code (PC) buildings). Buildings built to higher design standards (or retrofitted) are identified as Special High-Code (HS), Special Moderate-Code (MS), and Special Low-Code (LS) buildings (see Section 6). Within this section, methods for estimation of earthquake damage to buildings based on specific building type and an estimate of the level of ground shaking (or degree of ground failure) are described.

The scope of this section includes:

- Description of Specific Building Types (Section 5.3)
- Description of Building Damage States (None, Slight, Moderate, Extensive, and Complete) by specific building type (Section 5.3.3)
- Building Damage Due to Ground Shaking (Section 5.4)
- Building Damage Due to Ground Failure (Section 5.5)

This section focuses on functions for estimating building damage due to ground shaking. These building damage functions include: 1) fragility curves that describe the probability of reaching or exceeding different states of damage given peak building response, and 2) building capacity (push-over) curves that are used (with damping-modified demand spectra) to determine peak building response. For use in utility and transportation system damage evaluation, a separate set of building fragility curves expresses the probability of structural damage in terms of peak ground acceleration (PGA) and can be found in the Transportation and Utilities Sections (Section 7 and Section 8, respectively). Building damage functions for ground shaking are described in Section 5.4 for each specific building type.

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

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

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

5.1 Input Requirements and Output Information

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

- Specific building type (including height) and seismic design level that represents the building (or group of buildings) of interest, and
- Response spectrum (or PGA, for utility and transportation system buildings), and PGD for ground failure evaluation at the building's site or averaged across the Census tract where the building (or group of buildings) is located.

Typically, the specific building type and seismic design level is not known for each building and must be determined from the inventory of facilities using the relationship of building type, seismic zone, and occupancy. These relationships are provided in the Hazus Inventory Technical Manual. The response spectrum, PGA and PGD at the building site (or averaged across the Census tract) are Potential Earthquake Hazards (PEH) outputs, described in Section 4 of this document.

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

5.2 Form of Damage Functions

Hazus earthquake building damage functions are in the form of lognormal fragility curves that relate the probability of being in, or exceeding, a damage state for a given PEH demand parameter (e.g., response spectrum displacement). Figure 5-1 provides an example of fragility curves for the damage states used in this methodology.

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

Equation 5-1

$$\mathrm{S_d} = \bar{\mathrm{S}}_{\mathrm{d,ds}} * \varepsilon_{\mathrm{ds}}$$

Where:

$\bar{\mathrm{S}}_{\mathrm{d,ds}}$	is the median value of spectral displacement of damage state, ds, and
$\varepsilon_{\mathrm{ds}}$	is a lognormal random variable with unit median value and logarithmic standard deviation, β_{ds}

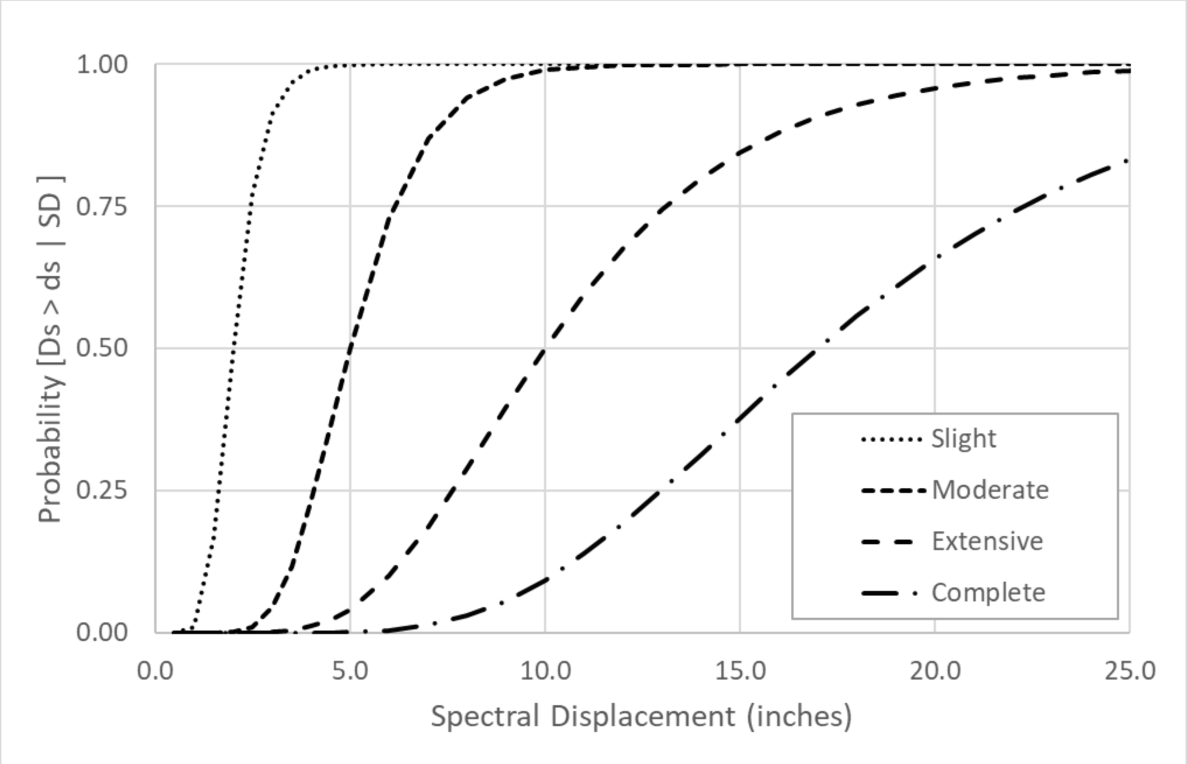


Figure 5-1 Example Fragility Curves for Slight, Moderate, Extensive, and Complete Damage States

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

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

Equation 5-2

$$\mathrm{P}[\mathrm{ds}|\mathrm{S_d}] = \Phi\left[\frac{1}{\beta_{\mathrm{ds}}}\ln\left(\frac{\mathrm{S_d}}{\overline{\mathrm{S}}_{\mathrm{d,ds}}}\right)\right]$$

Where:

$\overline{\mathrm{S}}_{\mathrm{d,ds}}$	is the median value of spectral displacement at which the building reaches the threshold of the damage state, ds
β_{ds}	is the standard deviation of the natural logarithm of spectral displacement for damage state, ds, and
Φ	is the standard normal cumulative distribution function.

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

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

- Uncertainty in the damage state threshold,
- Variability in the capacity (response) properties of the specific building type of interest, and
- Uncertainty in response due to the spatial variability of ground motion demand.

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

The fragility curves are driven by a PEH parameter. For ground failure, the PEH parameter used to drive fragility curves is PGD. For ground shaking, the PEH parameter used to drive building fragility curves is peak spectral response (either displacement or acceleration). PGA, rather than peak spectral displacement, is used to evaluate ground shaking-induced structural damage to buildings that are components of utility and transportation systems (see Section 5.4.3). Peak spectral response varies significantly for buildings that have different response properties (e.g., tall, flexible buildings will displace more than short, stiff buildings). Therefore, determination of peak spectral displacement requires knowledge of the building's response properties.

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

The demand spectrum is the 5% damped PEH input spectrum reduced for higher levels of effective damping (e.g., effective damping includes both elastic damping and hysteretic damping associated with post-yield cyclic response of the building).

Figure 5-2 illustrates the intersection of a typical building capacity curve and a typical demand spectrum (reduced for effective damping greater than 5% of critical). Design-, yield-, and ultimate-capacity points define the shape of building capacity curves. Peak building response (either spectral displacement or spectral acceleration) at the point of intersection of the capacity curve and demand spectrum is the parameter used with fragility curves to estimate damage state probabilities (see also Section 5.6.1.3).

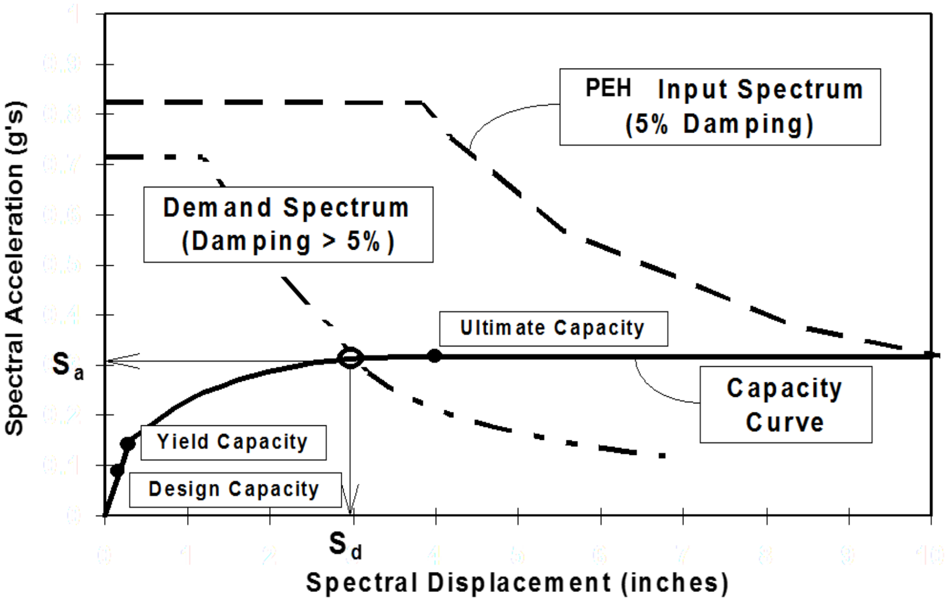


Figure 5-2 Example Building Capacity Curve and Demand Spectrum

5.3 Description of Specific Building Types

Table 5-1 lists the 36 specific building types that are used by the Hazus Methodology. These specific building types are based on the classification system of FEMA 178, *NEHRP Handbook for the Seismic Evaluation of Existing Buildings* (FEMA, 1992). In addition, the methodology breaks down FEMA 178 classes into height ranges and includes mobile homes.

Table 5-1 Specific Building Types

#	Label	Description	Height			
			Range		Typical	
			Name	Stories	Stories	Feet
1	W1	Wood, Light Frame (≤ 5,000 sq. ft.)		1 - 2	1	14
2	W2	Wood, Commercial & Industrial (> 5,000 sq. ft.)		All	2	24
3	S1L	Steel Moment Frame	Low-Rise	1 - 3	2	24
4	S1M		Mid-Rise	4 - 7	5	60
5	S1H		High-Rise	8+	13	156
6	S2L	Steel Braced Frame	Low-Rise	1 - 3	2	24
7	S2M		Mid-Rise	4 - 7	5	60
8	S2H		High-Rise	8+	13	156
9	S3	Steel Light Frame		All	1	15
10	S4L	Steel Frame with Cast-in-Place Concrete Shear Walls	Low-Rise	1 - 3	2	24
11	S4M		Mid-Rise	4 - 7	5	60
12	S4H		High-Rise	8+	13	156

#	Label	Description	Height			
			Range		Typical	
			Name	Stories	Stories	Feet
13	S5L	Steel Frame with Unreinforced Masonry Infill Walls	Low-Rise	1 - 3	2	24
14	S5M		Mid-Rise	4 – 7	5	60
15	S5H		High-Rise	8+	13	156
16	C1L	Concrete Moment Frame	Low-Rise	1 – 3	2	20
17	C1M		Mid-Rise	4 – 7	5	50
18	C1H		High-Rise	8+	12	120
19	C2L	Concrete Shear Walls	Low-Rise	1 - 3	2	20
20	C2M		Mid-Rise	4 – 7	5	50
21	C2H		High-Rise	8+	12	120
22	C3L	Concrete Frame with Unreinforced Masonry Infill Walls	Low-Rise	1 - 3	2	20
23	C3M		Mid-Rise	4 – 7	5	50
24	C3H		High-Rise	8+	12	120
25	PC1	Precast Concrete Tilt-Up Walls		All	1	15
26	PC2L	Precast Concrete Frames with Concrete Shear Walls	Low-Rise	1 - 3	2	20
27	PC2M		Mid-Rise	4 – 7	5	50
28	PC2H		High-Rise	8+	12	120
29	RM1L	Reinforced Masonry Bearing Walls with Wood or Metal Deck Diaphragms	Low-Rise	1-3	2	20
30	RM1M		Mid-Rise	4+	5	50
31	RM2L	Reinforced Masonry Bearing Walls with Precast Concrete Diaphragms	Low-Rise	1 - 3	2	20
32	RM2M		Mid-Rise	4 – 7	5	50
33	RM2H		High-Rise	8+	12	120
34	URML	Unreinforced Masonry Bearing Walls	Low-Rise	1 - 2	1	15
35	URMM		Mid-Rise	3+	3	35
36	MH	Mobile Homes		All	1	10

5.3.1 Structural Systems

A general description of each of the 16 structural systems of specific building types is given in the following sections. For additional information on the specific building types, including sketches of typical configurations, refer to FEMA 454, “Designing for Earthquakes: A Manual for Architects” (FEMA, 2006), available from the FEMA library.

Wood, Light Frame (W1)

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

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

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

Steel Moment Frame (S1)

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

Steel Braced Frame (S2)

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

Steel Light Frame (S3)

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

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

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

Steel Frame with Unreinforced Masonry Infill Walls (S5)

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

Reinforced Concrete Moment Resisting Frames (C1)

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

Concrete Shear Walls (C2)

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

Concrete Frame Buildings with Unreinforced Masonry Infill Walls (C3)

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

Precast Concrete Tilt-Up Walls (PC1)

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

Precast Concrete Frames with Concrete Shear Walls (PC2)

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

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

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

Reinforced Masonry Bearing Walls with Precast Concrete Diaphragms (RM2)

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

Unreinforced Masonry Bearing Walls (URM)

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

Mobile Homes (MH)

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

5.3.2 Nonstructural Components

Nonstructural components include a large variety of different architectural, mechanical, and electrical components (e.g., components listed in the NEHRP seismic design provisions for new buildings (FEMA, 1995a). Contents of the buildings are treated as a separate category. Nonstructural components are grouped as either "drift-sensitive" or "acceleration-sensitive" components, in order to assess their damage due to an earthquake. Damage to drift-sensitive nonstructural components is primarily a function of inter-story drift; damage to acceleration-sensitive nonstructural components and building contents is primarily a function of floor acceleration. Table 5-2 lists typical nonstructural components and building contents and identifies each item as drift-sensitive or acceleration-sensitive.

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

Table 5-2 List of Typical Nonstructural Components and Contents of Buildings

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

**Primary cause of damage is indicated by "P", secondary cause of damage is indicated by "S"*

5.3.3 Description of Building Damage States

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

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

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

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

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

The Methodology predicts structural and nonstructural damage states in terms of one of five ranges of damage or “Damage States”: None, Slight, Moderate, Extensive, and Complete. For example, the Slight damage state extends from the threshold of Slight damage up to the threshold of Moderate damage. General descriptions of these damage states are provided for all specific building types with reference to observable damage incurred by structural (Section 5.3.3.1) and nonstructural building components (Section 5.3.3.2). Damage predictions resulting from this physical damage estimation method are then expressed in terms of the probability of a building being in any of these five damage states.

5.3.3.1 Structural Damage

Descriptions for the Slight, Moderate, Extensive, and Complete structural damage states for the 16 basic specific building types are provided below; no descriptions are included for the “None” damage state. For estimating casualties, the descriptions of Complete damage include the fraction of the total floor area of each specific building type that is likely to collapse. Collapse fractions are based on judgment and limited earthquake data, considering the material and construction of different specific building types.

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

Wood, Light Frame (W1)

- **Slight Structural Damage**: Small plaster or gypsum-board cracks at corners of door and window openings and wall-ceiling intersections; small cracks in masonry chimneys and masonry veneer.
- **Moderate Structural Damage**: Large plaster or gypsum-board cracks at corners of door and window openings; small diagonal cracks across shear wall panels exhibited by small cracks in stucco and gypsum wall panels; large cracks in brick chimneys; toppling of tall masonry chimneys.
- **Extensive Structural Damage**: Large diagonal cracks across shear wall panels or large cracks at plywood joints; permanent lateral movement of floors and roof; toppling of most brick chimneys; cracks in foundations; splitting of wood sill plates and/or slippage of structure over foundations; partial collapse of “room-over-garage” or other “soft-story” configurations; small foundations cracks.
- **Complete Structural Damage**: Structure may have large permanent lateral displacement, may collapse, or be in imminent danger of collapse due to cripple wall failure or the failure of the lateral load-resisting system; some structures may slip and fall off the foundations; large foundation cracks. Approximately 3% of the total area of W1 buildings with Complete damage is expected to be collapsed.

Wood, Commercial and Industrial (W2)

- **Slight Structural Damage:** Small cracks at corners of door and window openings and wall-ceiling intersections; small cracks on stucco and plaster walls. Some slippage may be observed at bolted connections.
- **Moderate Structural Damage**: Larger cracks at corners of door and window openings; small diagonal cracks across shear wall panels exhibited by cracks in stucco and gypsum wall panels; minor slack (less than 1/8 inch extension) in diagonal rod bracing requiring re-tightening; minor lateral offset at store fronts and other large openings; small cracks or wood splitting may be observed at bolted connections.
- **Extensive Structural Damage**: Large diagonal cracks across shear wall panels; large slack in diagonal rod braces and/or broken braces; permanent lateral movement of floors and roof; cracks in foundations; splitting of wood sill plates and/or slippage of structure over foundations; partial collapse of “soft-story” configurations; bolt slippage and wood splitting at bolted connections.
- **Complete Structural Damage**: Structure may have large permanent lateral displacement, may collapse or be in imminent danger of collapse due to failed shear walls, broken brace rods or failed framing connections; it may fall off its foundations; large cracks in the foundations. Approximately 3% of the total area of W2 buildings with Complete damage is expected to be collapsed.

Steel Moment Frame (S1)

- **Slight Structural Damage**: Minor deformations in connections or hairline cracks in a few welds.
- **Moderate Structural Damage**: Some steel members have yielded, exhibiting observable permanent rotations at connections; a few welded connections may exhibit major cracks through welds or a few bolted connections may exhibit broken bolts or enlarged bolt holes.

- **Extensive Structural Damage**: Most steel members have exceeded their yield capacity, resulting in significant permanent lateral deformation of the structure. Some of the structural members or connections may have exceeded their ultimate capacity, exhibited by major permanent member rotations at connections, buckled flanges, and failed connections. Partial collapse of portions of structure is possible due to failed critical elements and/or connections.
- **Complete Structural Damage**: A significant portion of the structural elements have exceeded their ultimate capacities or some critical structural elements or connections have failed, resulting in dangerous permanent lateral displacement, partial collapse or collapse of the building. Approximately 8% (low-rise), 5% (mid-rise) or 3% (high-rise) of the total area of S1 buildings with Complete damage is expected to be collapsed.

Steel Braced Frame (S2)

- **Slight Structural Damage**: A few steel braces have yielded, which may be indicated by minor stretching and/or buckling of slender brace members; minor cracks in welded connections; minor deformations in bolted brace connections.
- **Moderate Structural Damage**: Some steel braces have yielded, exhibiting observable stretching and/or buckling of braces; a few braces, other members or connections have indications of reaching their ultimate capacity, exhibited by buckled braces, cracked welds, or failed bolted connections.
- **Extensive Structural Damage**: Most steel brace and other members have exceeded their yield capacity, resulting in significant permanent lateral deformation of the structure. Some structural members or connections have exceeded their ultimate capacity, exhibited by buckled or broken braces, flange buckling, broken welds, or failed bolted connections. Anchor bolts at columns may be stretched. Partial collapse of portions of the structure is possible due to failure of critical elements or connections.
- **Complete Structural Damage**: Most of the structural elements have reached their ultimate capacities or some critical members or connections have failed, resulting in dangerous permanent lateral deflection, partial collapse or collapse of the building. Approximately 8% (low-rise), 5% (mid-rise), or 3% (high-rise) of the total area of S2 buildings with Complete damage is expected to be collapsed.

Steel Light Frame (S3)

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

- **Slight Structural Damage**: A few steel rod braces have yielded, which may be indicated by minor sagging of rod braces. Minor cracking at welded connections or minor deformations at bolted connections of moment frames may be observed.
- **Moderate Structural Damage**: Most steel rod braces have yielded, exhibiting observable significantly sagging rod braces; a few brace connections may be broken. Some weld cracking may be observed in the moment frame connections.
- **Extensive Structural Damage**: Significant permanent lateral deformation of the structure due to broken brace rods, stretched anchor bolts, and permanent deformations at moment

frame members. Some screw or welded attachments of roof and wall siding to steel framing may be broken. Some purlin and girt connections may be broken.

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

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

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

- **Slight Structural Damage**: Diagonal hairline cracks on most concrete shear wall surfaces; minor concrete spalling at a few locations.
- **Moderate Structural Damage**: Most shear wall surfaces exhibit diagonal cracks; some of the shear walls have exceeded their yield capacities, as exhibited by larger diagonal cracks and concrete spalling at wall ends.
- **Extensive Structural Damage**: Most concrete shear walls have exceeded their yield capacities; a few walls have reached or exceeded their ultimate capacity, as exhibited by large through-the-wall diagonal cracks, extensive spalling around the cracks, and visibly buckled wall reinforcement. Partial collapse may occur due to failed connections of steel framing to concrete walls. Some damage may be observed in steel frame connections.
- **Complete Structural Damage**: Structure may be collapsed or in danger of collapse due to total failure of shear walls and loss of stability of the steel frames. Approximately 8% (low-rise), 5% (mid-rise) or 3% (high-rise) of the total area of S4 buildings with Complete damage is expected to be collapsed.

Steel Frame with Unreinforced Masonry Infill Walls (S5)

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

- **Slight Structural Damage**: Diagonal (sometimes horizontal) hairline cracks on most infill walls; cracks at frame-infill interfaces.
- **Moderate Structural Damage**: Most infill wall surfaces exhibit larger diagonal or horizontal cracks; some walls exhibit crushing of brick around beam-column connections.
- **Extensive Structural Damage**: Most infill walls exhibit large cracks; some bricks may be dislodged and fall; some infill walls may bulge out-of-plane; a few walls may fall off partially or fully; some steel frame connections may have failed. Structure may exhibit permanent lateral deformation or partial collapse due to failure of some critical members.
- **Complete Structural Damage**: Structure is collapsed or in danger of imminent collapse due to total failure of many infill walls and loss of stability of the steel frames. Approximately

8% (low-rise), 5% (mid-rise) or 3% (high-rise) of the total area of S5 buildings with Complete damage is expected to be collapsed.

Reinforced Concrete Moment Resisting Frames (C1)

- **Slight Structural Damage**: Flexural or shear type hairline cracks in some beams and columns near joints or within joints.
- **Moderate Structural Damage**: Most beams and columns exhibit hairline cracks. In ductile frames, some of the frame elements have reached yield capacity, as indicated by larger flexural cracks and some concrete spalling. Nonductile frames may exhibit larger shear cracks and spalling.
- **Extensive Structural Damage**: Some of the frame elements have reached their ultimate capacity, as indicated in ductile frames by large flexural cracks, spalled concrete, and buckled main reinforcement; nonductile frame elements may have suffered shear failures or bond failures at reinforcement splices, broken ties or buckled main reinforcement in columns which may result in partial collapse.
- **Complete Structural Damage**: Structure is collapsed or in imminent danger of collapse due to brittle failure of nonductile frame elements or loss of frame stability. Approximately 13% (low-rise), 10% (mid-rise) or 5% (high-rise) of the total area of C1 buildings with Complete damage is expected to be collapsed.

Concrete Shear Walls (C2)

- **Slight Structural Damage**: Diagonal hairline cracks on most concrete shear wall surfaces; minor concrete spalling at a few locations.
- **Moderate Structural Damage**: Most shear wall surfaces exhibit diagonal cracks; some shear walls have exceeded yield capacity, as indicated by larger diagonal cracks and concrete spalling at wall ends.
- **Extensive Structural Damage**: Most concrete shear walls have exceeded their yield capacities; some walls have exceeded their ultimate capacities, as indicated by large, through-the-wall diagonal cracks, extensive spalling around the cracks, and visibly buckled wall reinforcement or rotation of narrow walls with inadequate foundations. Partial collapse may occur due to failure of nonductile columns not designed to resist lateral loads.
- **Complete Structural Damage**: Structure has collapsed or is in imminent danger of collapse due to failure of most of the shear walls and failure of some critical beams or columns. Approximately 13% (low-rise), 10% (mid-rise) or 5% (high-rise) of the total area of C2 buildings with Complete damage is expected to be collapsed.

Concrete Frame Buildings with Unreinforced Masonry Infill Walls (C3)

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

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

- **Moderate Structural Damage**: Most infill wall surfaces exhibit larger diagonal or horizontal cracks; some walls exhibit crushing of brick around beam-column connections. Diagonal shear cracks may be observed in concrete beams or columns.
- **Extensive Structural Damage**: Most infill walls exhibit large cracks; some bricks may dislodge and fall; some infill walls may bulge out-of-plane; a few walls may fall partially or fully; a few concrete columns or beams may fail in shear resulting in partial collapse. Structure may exhibit permanent lateral deformation.
- **Complete Structural Damage**: Structure has collapsed or is in imminent danger of collapse due to a combination of total failure of the infill walls and nonductile failure of the concrete beams and columns. Approximately 15% (low-rise), 13% (mid-rise) or 5% (high-rise) of the total area of C3 buildings with Complete damage is expected to be collapsed.

Precast Concrete Tilt-Up Walls (PC1)

- **Slight Structural Damage**: Diagonal hairline cracks on concrete shear wall surfaces; larger cracks around door and window openings in walls with a large proportion of openings; minor concrete spalling at a few locations; minor separation of walls from the floor and roof diaphragms; hairline cracks around metal connectors between wall panels and at connections of beams to walls.
- **Moderate Structural Damage**: Most wall surfaces exhibit diagonal cracks; larger cracks in walls with door or window openings; a few shear walls have exceeded their yield capacities, as indicated by larger diagonal cracks and concrete spalling. Cracks may appear at top of walls near panel intersections, indicating “chord” yielding. Some walls may have visibly pulled away from the roof. Some welded panel connections may have been broken, as indicated by spalled concrete around connections. Some spalling may be observed at the connections of beams to walls.
- **Extensive Structural Damage**: In buildings with relatively large area of wall openings, most concrete shear walls have exceeded their yield capacities and some have exceeded their ultimate capacities as indicated by large, through-the-wall diagonal cracks, extensive spalling around the cracks, and visibly buckled wall reinforcement. The plywood diaphragms may exhibit cracking and separation along plywood joints. Partial collapse of the roof may result from the failure of the wall-to-diaphragm anchorages sometimes with falling of wall panels.
- **Complete Structural Damage**: Structure is collapsed or is in imminent danger of collapse due to failure of the wall-to-roof anchorages, splitting of ledgers, or failure of plywood-to-ledger nailing, failure of beam connections at walls, failure of roof or floor diaphragms, or, failure of the wall panels. Approximately 15% of the total area of PC1 buildings with Complete damage is expected to be collapsed.

Precast Concrete Frames with Concrete Shear Walls (PC2)

- **Slight Structural Damage**: Diagonal hairline cracks on most shear wall surfaces; minor concrete spalling at a few connections of precast members.
- **Moderate Structural Damage**: Most shear wall surfaces exhibit diagonal cracks; some shear walls have exceeded their yield capacities, as indicated by larger cracks and concrete spalling at wall ends; observable distress or movement at connections of precast frame connections, some failures at metal inserts and welded connections.

- **Extensive Structural Damage**: Most concrete shear walls have exceeded their yield capacities; some walls may have reached their ultimate capacities indicated by large, through-the-wall diagonal cracks, extensive spalling around the cracks and visibly buckled wall reinforcement. Some critical precast frame connections may have failed, resulting in partial collapse.
- **Complete Structural Damage**: Structure has collapsed or is in imminent danger of collapse due to failure of the shear walls and/or failures at precast frame connections. Approximately 15% (low-rise), 13% (mid-rise) or 10% (high-rise) of the total area of PC2 buildings with Complete damage is expected to be collapsed.

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

- **Slight Structural Damage**: Diagonal hairline cracks on masonry wall surfaces; larger cracks around door and window openings in walls with a large proportion of openings; minor separation of walls from the floor and roof diaphragms.
- **Moderate Structural Damage**: Most wall surfaces exhibit diagonal cracks; some of the shear walls have exceeded their yield capacities, as indicated by larger diagonal cracks. Some walls may have visibly pulled away from the roof.
- **Extensive Structural Damage**: In buildings with a relatively large area of wall openings, most shear walls have exceeded their yield capacities and some of the walls have exceeded their ultimate capacities as indicated by large, through-the-wall diagonal cracks and visibly buckled wall reinforcement. The plywood diaphragms may exhibit cracking and separation along plywood joints. Partial collapse of the roof may result from failure of the wall-to-diaphragm anchorages or the connections of beams to walls.
- **Complete Structural Damage**: Structure has collapsed or is in imminent danger of collapse due to failure of the wall anchorages or due to failure of the wall panels. Approximately 13% (low-rise) or 10% (mid-rise) of the total area of RM1 buildings with Complete damage is expected to be collapsed.

Reinforced Masonry Bearing Walls with Precast Concrete Diaphragms (RM2)

- **Slight Structural Damage**: Diagonal hairline cracks on masonry wall surfaces; larger cracks around door and window openings in walls with large proportion of openings.
- **Moderate Structural Damage**: Most wall surfaces exhibit diagonal cracks; some of the shear walls have exceeded their yield capacities, as indicated by larger cracks.
- **Extensive Structural Damage**: In buildings with a relatively large area of wall openings, most shear walls have exceeded their yield capacities and some of the walls have exceeded their ultimate capacities, as exhibited by large, through-the-wall diagonal cracks and visibly buckled wall reinforcement. The diaphragms may also exhibit cracking.
- **Complete Structural Damage**: Structure is collapsed or is in imminent danger of collapse due to failure of the walls. Approximately 13% (low-rise), 10% (mid-rise) or 5% (high-rise) of the total area of RM2 buildings with Complete damage is expected to be collapsed.

Unreinforced Masonry Bearing Walls (URM)

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

- **Moderate Structural Damage**: Most wall surfaces exhibit diagonal cracks; some of the walls exhibit larger diagonal cracks; masonry walls may have visible separation from diaphragms; significant cracking of parapets; some masonry may fall from walls or parapets.
- **Extensive Structural Damage**: In buildings with a relatively large area of wall openings, most walls have suffered extensive cracking. Some parapets and gable end walls have fallen. Beams or trusses may have moved relative to their supports.
- **Complete Structural Damage**: Structure has collapsed or is in imminent danger of collapse due to in-plane or out-of-plane failure of the walls. Approximately 15% of the total area of URM buildings with Complete damage is expected to be collapsed.

Mobile Homes (MH)

- **Slight Structural Damage**: Damage to some porches, stairs or other attached components.
- **Moderate Structural Damage**: Major movement of the mobile home over its supports, resulting in some damage to metal siding and stairs and requiring resetting of the mobile home on its supports.
- **Extensive Structural Damage**: Mobile home has fallen partially off its supports, often severing utility lines.
- **Complete Structural Damage**: Mobile home has totally fallen off its supports; usually severing utility lines, with steep jack stands penetrating through the floor. Approximately 3% of the total area of MH buildings with Complete damage is expected to be collapsed.

5.3.3.2 Nonstructural Damage

Five damage states are used to describe nonstructural damage: None, Slight, Moderate, Extensive, and Complete nonstructural damage. Nonstructural damage is considered to be independent of the structural specific building type (i.e., partitions, ceilings, cladding, etc. are assumed to incur the same damage when subjected to the same inter-story drift or floor acceleration whether they are in a steel frame building or in a concrete shear wall building), consequently, building-specific damage state descriptions are not meaningful. Instead, general descriptions of nonstructural damage states are provided for common nonstructural systems.

Damage to drift-sensitive nonstructural components (e.g., full-height drywall partitions) is primarily a function of inter-story drift, while for acceleration-sensitive components (e.g., mechanical equipment) damage is a function of the floor acceleration. Developing fragility curves for each possible nonstructural component is not practicable for the purposes of regional loss estimation and there is insufficient data to develop such fragility curves. Hence, in this methodology, nonstructural building components are grouped into drift-sensitive and acceleration-sensitive component groups, and the damage functions estimated for each group are assumed to be "typical" of its sub-components. However, that damage depends on the anchorage/bracing provided to the nonstructural components. Damageability characteristics of each group are described by a set of fragility curves (see Sections 5.4.2.5 and 5.4.2.6).

The type of nonstructural components in a given building is a function of the building occupancy-use classification. For example, single-family residences would not have curtain wall panels, suspended ceilings, elevators, etc., while these items would be found in an office building. Hence, the relative values of nonstructural components in relation to the overall building replacement value vary with type of occupancy. In Section 11.2 on Direct Economic Losses, estimates of the replacement cost breakdown between structural building components for different occupancy-use classifications are provided; further breakdowns are provided by drift- and acceleration-sensitive nonstructural components.

In the following, general descriptions of the four nonstructural damage states (not including the None damage state) are described for common nonstructural building components:

Partitions Walls

- **Slight Nonstructural Damage**: A few cracks are observed at intersections of walls and ceilings and at corners of door openings.
- **Moderate Nonstructural Damage**: Larger and more extensive cracks requiring repair and repainting; some partitions may require replacement of gypsum board or other finishes.
- **Extensive Nonstructural Damage**: Most of the partitions are cracked and a significant portion may require replacement of finishes; some door frames in the partitions are also damaged and require re-setting.
- **Complete Nonstructural Damage**: Most partition finish materials and framing may have to be removed and replaced, damaged studs repaired, and walls refinished. Most door frames may also have to be repaired and replaced.

Suspended Ceilings

- **Slight Nonstructural Damage**: A few ceiling tiles have moved or fallen down.
- **Moderate Nonstructural Damage**: Falling of tiles is more extensive; in addition, the ceiling support framing (T-bars) has disconnected and/or buckled at a few locations; lenses have fallen off some light fixtures and a few fixtures have fallen; localized repairs are necessary.
- **Extensive Nonstructural Damage**: The ceiling system exhibits extensive buckling, disconnected T-bars and falling ceiling tiles; ceiling partially collapses at a few locations and some light fixtures fall; repair typically involves removal of most or all ceiling tiles.
- **Complete Nonstructural Damage**: The ceiling system is buckled throughout and/or fallen and requires complete replacement; many light fixtures fall.

Exterior Wall Panels

- **Slight Nonstructural Damage**: Slight movement of the panels, requiring realignment.
- **Moderate Nonstructural Damage**: The movements are more extensive; connections of panels to structural frame are damaged requiring further inspection and repairs; some window frames may need realignment.
- **Extensive Nonstructural Damage**: Most of the panels are cracked or otherwise damaged and misaligned, and most panel connections to the structural frame are damaged requiring thorough review and repairs; a few panels fall or are in imminent danger of falling; some window panes are broken and some pieces of glass have fallen.
- **Complete Nonstructural Damage**: Most panels are severely damaged, most connections are broken or severely damaged, some panels have fallen and most are in imminent danger of falling; extensive glass breakage and falling.

Electrical-Mechanical Equipment, Piping, Ducts

- **Slight Nonstructural Damage**: The most vulnerable equipment (e.g., unanchored or mounted on spring isolators) moves and damages attached piping or ducts.
- **Moderate Nonstructural Damage**: Movements are larger and damage is more extensive; piping leaks occur at a few locations; elevator machinery and rails may require realignment.
- **Extensive Nonstructural Damage**: Equipment on spring isolators topples and falls; other unanchored equipment slides or falls, breaking connections to piping and ducts; leaks develop at many locations; anchored equipment indicate stretched bolts or strain at anchorages.
- **Complete Nonstructural Damage**: Equipment is damaged by sliding, overturning or failure of their supports and is not operable; piping is leaking at many locations; some pipe and duct supports have failed, causing pipes and ducts to fall or hang down; elevator rails are buckled or have broken supports and/or counterweights have derailed.

5.4 Building Damage Due to Ground Shaking

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

Capacity curves and fragility curves for High-Code, Moderate-Code, Low-Code, and Pre-Code buildings are based on modern building code requirements (e.g., 1976 *Uniform Building Code*, 1985 *NEHRP Provisions*, or later editions of these model codes). The design criteria for various seismic design zones are shown in Table 5-3. Additional description of seismic levels may be found in Section 5.7.

Table 5-3 Approximate Basis for Seismic Design Levels

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

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

5.4.1 Capacity Curves

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

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

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

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

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

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

Up to the yield point, the building capacity curve is assumed to be linear with stiffness based on an estimate of the true period of the building. The true period is typically longer than the code-specified period of the building due to the flexing of diaphragms of short, stiff buildings, flexural cracking of elements of concrete and masonry structures, flexibility of foundations, and other factors observed to affect building stiffness. From the yield point to the ultimate point, the capacity curve transitions in slope from an essentially elastic state to a fully plastic state. The capacity curve is assumed to remain plastic past the ultimate point. An example building capacity curve is shown in Figure 5 3.

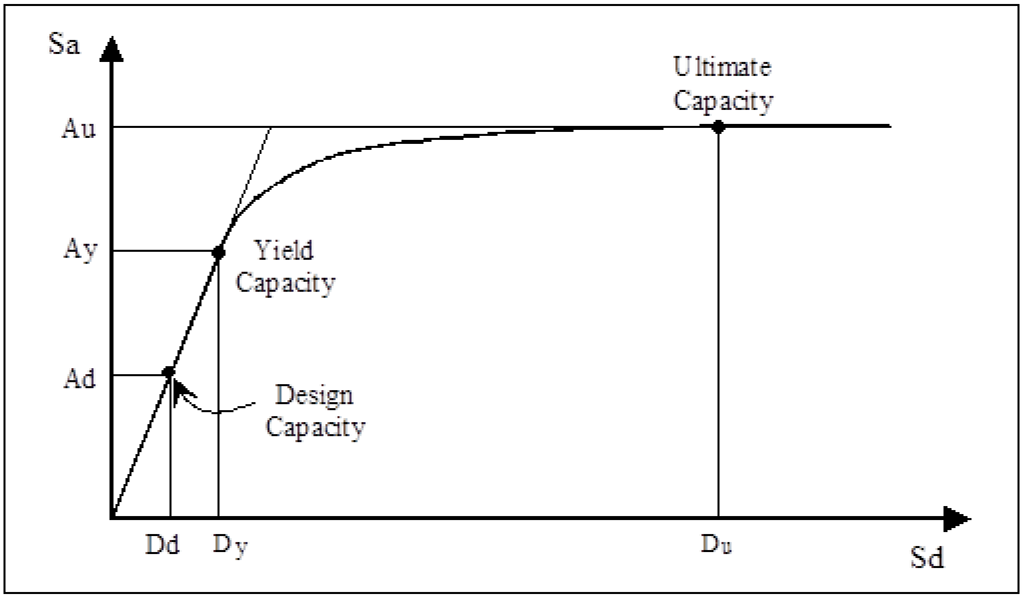


Figure 5-3 Example Building Capacity Curve

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

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

The design strength, C_s, is approximately based on the lateral-force design requirements of current seismic codes (e.g., 1994 *NEHRP Provisions*). These requirements are a function of the building's seismic zone location and other factors include: site soil condition, type of lateral force-resisting system, and building period. For each of the four basic design levels (High-Code, Moderate-Code, Low-Code, and Pre-Code), design capacity is based on the best estimate of typical design properties. Table 5-4summarizes design capacity for each building type and design level. Building period, Te, push-over mode parameters α_1 and α_2, the ratio of yield to design strength, γ, and the ratio of ultimate to yield strength, λ, are assumed to be independent of design level. Values of these parameters are summarized in Table 5-5 for each building type. Values of the "ductility" factor, μ, are given in Table 5-6 for each building type and design level. Note that for the following tables, shaded boxes indicate types that are not permitted by current seismic codes.

Table 5-4 Code Building Capacity Parameters - Design Strength (C_s)

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

*Shaded boxes with an asterisk (*) indicate types that are not permitted by current seismic codes.

Table 5-5 Code Building Capacity Parameters - Period (T_e), Pushover Mode Response Factors (α_1, α_2) and Overstrength Ratios (γ, λ)

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

Table 5-6 Code Building Capacity Parameter - Ductility (μ)

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

**Shaded boxes with an asterisk (*) indicate types that are not permitted by current seismic codes.*

Building capacity curves are assumed to have a range of possible properties that are lognormally distributed as a function of the ultimate strength (Au) of each capacity curve. Capacity curves described by the values of parameters given in Table 5-4, Table 5-5, and Table 5-6 represent median estimates of building capacity. The variability of the capacity of each building type is assumed to be: β(Au) = 0.25 for code-designed buildings (High-Code, Moderate-Code, and Low-Code seismic design levels) and β(Au)= 0.30 for Pre-Code buildings.

Example construction of median, 84th percentile (+1 β), and 16th percentile (-1 β) building capacity curves for a typical building is illustrated in Figure 5-4. Median capacity curves are intersected with demand spectra to estimate peak building response. The variability of the capacity curves is used, with other sources of variability and uncertainty, to define total fragility curve variability.

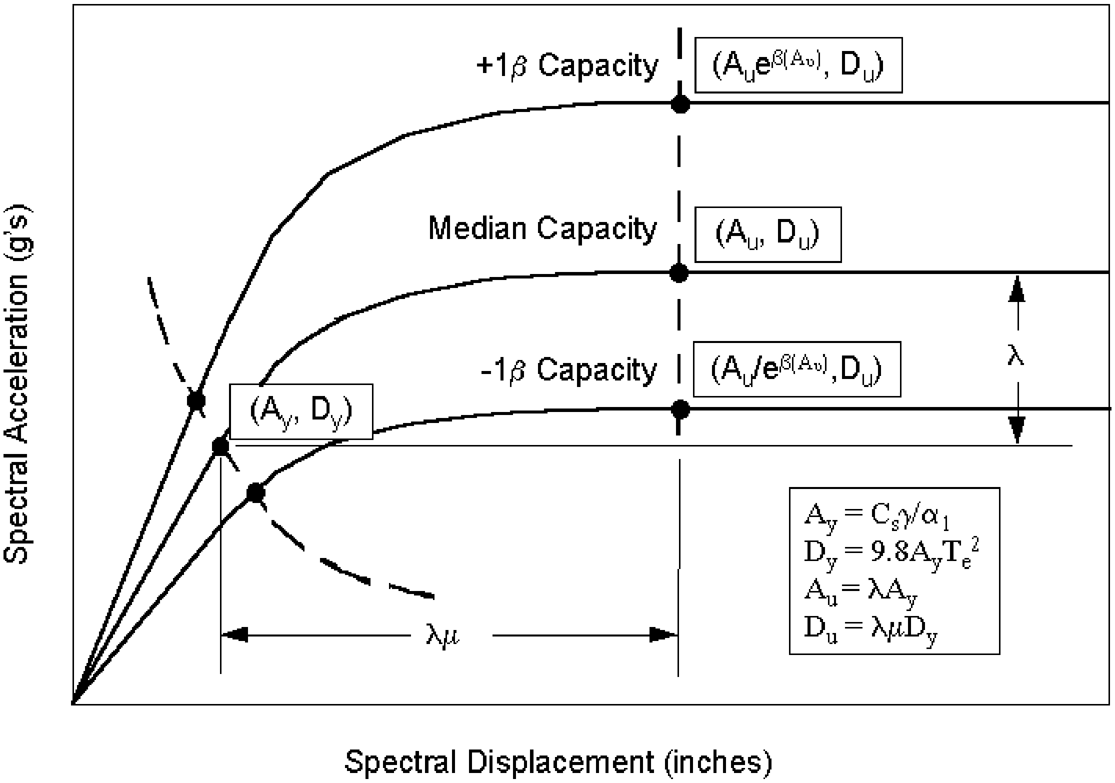


Figure 5-4 Example Construction of Median, +1β and -1β Building Capacity Curves

Table 5-7, Table 5-8, Table 5-9, and Table 5-10 summarize yield capacity and ultimate capacity control points for High-Code, Moderate-Code, Low-Code, and Pre-Code seismic design levels, respectively. Note that for the following tables, shaded boxes indicate types that are not permitted by current seismic codes.

Table 5-7 Code Building Capacity Curves – High-Code Seismic Design Level

Building Type	Yield Capacity Point		Ultimate Capacity Point	
	D_y (in.)	A_y (g)	D_u (in.)	A_u (g)
W1	0.48	0.400	11.51	1.200
W2	0.626	0.400	12.528	1.000
S1L	0.611	0.250	14.667	0.749
S1M	1.775	0.156	28.40	0.468
S1H	4.657	0.098	55.884	0.293
S2L	0.626	0.400	10.023	0.800
S2M	2.426	0.333	25.876	0.667
S2H	7.746	0.254	61.965	0.508
S3	0.626	0.400	10.023	0.800
S4L	0.384	0.320	6.906	0.720
S4M	1.092	0.267	13.10	0.600
S4H	3.486	0.203	31.37	0.457
S5L*	0.12*	0.100*	1.199*	0.200*
S5M*	0.341*	0.083*	2.274*	0.167*
S5H*	1.089*	0.063*	5.446*	0.127*
C1L	0.391	0.250	9.387	0.749
C1M	1.152	0.208	18.436	0.624
C1H	2.011	0.098	24.13	0.293
C2L	0.48	0.400	9.592	1.000
C2M	1.038	0.333	13.841	0.833
C2H	2.939	0.254	29.394	0.635
C3L*	0.12*	0.100*	1.349*	0.225*
C3M*	0.26*	0.083*	1.946*	0.188*
C3H*	0.735*	0.063*	4.134*	0.143*
PC1	0.719	0.600	11.51	1.200
PC2L	0.48	0.400	7.673	0.800
PC2M	1.038	0.333	11.073	0.667
PC2H	2.939	0.254	23.515	0.508
RM1L	0.639	0.533	10.229	1.066
RM1M	1.384	0.444	14.76	0.889
RM2L	0.639	0.533	10.229	1.066
RM2M	1.384	0.444	14.76	0.889
RM2H	3.918	0.338	31.346	0.677
URML*	0.24*	0.200*	2.397*	0.400*
URMM*	0.272*	0.111	1.812*	0.222*
MH	0.18	0.150	2.158	0.300

**Shaded boxes and building types with an asterisk (*) indicate types that are not permitted by current seismic codes.*

Table 5-8 Code Building Capacity Curves – Moderate-Code Seismic Design Level

Building Type	Yield Capacity Point		Ultimate Capacity Point	
	D_y (in.)	A_y (g)	D_u (in.)	A_u (g)
W1	0.36	0.300	6.475	0.900
W2	0.313	0.200	4.698	0.500
S1L	0.306	0.125	5.50	0.375
S1M	0.888	0.078	10.651	0.234
S1H	2.329	0.049	20.957	0.147
S2L	0.313	0.200	3.758	0.400
S2M	1.213	0.167	9.704	0.333
S2H	3.873	0.127	23.237	0.254
S3	0.313	0.200	3.758	0.400
S4L	0.192	0.160	2.59	0.360
S4M	0.546	0.133	4.913	0.300
S4H	1.743	0.102	11.764	0.228
S5L*	0.12*	0.100*	1.199*	0.200*
S5M*	0.341*	0.083*	2.274*	0.167*
S5H*	1.089*	0.063*	5.446*	0.127*
C1L	0.196	0.125	3.52	0.375
C1M	0.576	0.104	6.914	0.312
C1H	1.005	0.049	9.049	0.147
C2L	0.24	0.200	3.597	0.500
C2M	0.519	0.167	5.191	0.417
C2H	1.47	0.127	11.023	0.317
C3L*	0.12*	0.100*	1.349*	0.225*
C3M*	0.26*	0.083*	1.946*	0.188*
C3H*	0.735*	0.063*	4.134*	0.143*
PC1	0.36	0.300	4.316	0.600
PC2L	0.24	0.200	2.878	0.400
PC2M	0.519	0.167	4.153	0.333
PC2H	1.47	0.127	8.818	0.254
RM1L	0.32	0.267	3.836	0.533
RM1M	0.692	0.222	5.535	0.444
RM2L	0.32	0.267	3.836	0.533
RM2M	0.692	0.222	5.535	0.444
RM2H	1.959	0.169	11.755	0.338
URML*	0.24*	0.200*	2.397*	0.400*
URMM*	0.272*	0.111*	1.812*	0.222*
MH	0.18	0.150	2.158	0.300

**Shaded boxes and building types with an asterisk (*) indicate types that are not permitted by current seismic codes*

Table 5-9 Code Building Capacity Curves – Low-Code Seismic Design Level

Building Type	Yield Capacity Point		Ultimate Capacity Point	
	D_y (in.)	A_y (g)	D_u (in.)	A_u (g)
W1	0.24	0.200	4.316	0.600
W2	0.157	0.100	2.349	0.250
S1L	0.153	0.062	2.292	0.187
S1M	0.444	0.039	4.437	0.117
S1H	1.164	0.024	8.732	0.073
S2L	0.157	0.100	1.566	0.200
S2M	0.607	0.083	4.043	0.167
S2H	1.936	0.063	9.682	0.127
S3	0.157	0.100	1.566	0.200
S4L	0.096	0.080	1.079	0.180
S4M	0.273	0.067	2.047	0.150
S4H	0.871	0.051	4.902	0.114
S5L	0.12	0.100	1.199	0.200
S5M	0.341	0.083	2.274	0.167
S5H	1.089	0.063	5.446	0.127
C1L	0.098	0.062	1.467	0.187
C1M	0.288	0.052	2.881	0.156
C1H	0.503	0.024	3.77	0.073
C2L	0.12	0.100	1.499	0.250
C2M	0.26	0.083	2.163	0.208
C2H	0.735	0.063	4.593	0.159
C3L	0.12	0.100	1.349	0.225
C3M	0.26	0.083	1.946	0.188
C3H	0.735	0.063	4.134	0.143
PC1	0.18	0.150	1.798	0.300
PC2L	0.12	0.100	1.199	0.200
PC2M	0.26	0.083	1.73	0.167
PC2H	0.735	0.063	3.674	0.127
RM1L	0.16	0.133	1.598	0.267
RM1M	0.346	0.111	2.306	0.222
RM2L	0.16	0.133	1.598	0.267
RM2M	0.346	0.111	2.306	0.222
RM2H	0.98	0.085	4.898	0.169
URML	0.24	0.200	2.397	0.400
URMM	0.272	0.111	1.812	0.222
MH	0.18	0.150	2.158	0.300

Table 5-10 Building Capacity Curves – Pre-Code Seismic Design Level

Building Type	Yield Capacity Point		Ultimate Capacity Point	
	D_y (in.)	A_y (g)	D_u (in.)	A_u (g)
W1	0.24	0.200	4.316	0.600
W2	0.157	0.100	2.349	0.250
S1L	0.153	0.062	2.292	0.187
S1M	0.444	0.039	4.437	0.117
S1H	1.164	0.024	8.732	0.073
S2L	0.157	0.100	1.566	0.200
S2M	0.607	0.083	4.043	0.167
S2H	1.936	0.063	9.682	0.127
S3	0.157	0.100	1.566	0.200
S4L	0.096	0.080	1.079	0.180
S4M	0.273	0.067	2.047	0.150
S4H	0.871	0.051	4.902	0.114
S5L	0.12	0.100	1.199	0.200
S5M	0.341	0.083	2.274	0.167
S5H	1.089	0.063	5.446	0.127
C1L	0.098	0.062	1.467	0.187
C1M	0.288	0.052	2.881	0.156
C1H	0.503	0.024	3.77	0.073
C2L	0.12	0.100	1.499	0.250
C2M	0.26	0.083	2.163	0.208
C2H	0.735	0.063	4.593	0.159
C3L	0.12	0.100	1.349	0.225
C3M	0.26	0.083	1.946	0.188
C3H	0.735	0.063	4.134	0.143
PC1	0.18	0.150	1.798	0.300
PC2L	0.12	0.100	1.199	0.200
PC2M	0.26	0.083	1.73	0.167
PC2H	0.735	0.063	3.674	0.127
RM1L	0.16	0.133	1.598	0.267
RM1M	0.346	0.111	2.306	0.222
RM2L	0.16	0.133	1.598	0.267
RM2M	0.346	0.111	2.306	0.222
RM2H	0.98	0.085	4.898	0.169
URML	0.24	0.200	2.397	0.400
URMM	0.272	0.111	1.812	0.222
MH	0.09	0.075	0.719	0.150

5.4.2 Fragility Curves

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

5.4.2.1 Background

The probability of being in or exceeding a given damage state is modeled as a cumulative lognormal distribution. For structural damage, given the spectral displacement, S_d, the probability of being in or exceeding a damage state, is modeled as:

Equation 5-3

$$P[ds|S_d] = \Phi\left[\frac{1}{\beta_{ds}}\ln\left(\frac{S_d}{\bar{S}_{d,ds}}\right)\right]$$

Where:

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

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

Φ is the standard normal cumulative distribution function.

For example, a mid-rise, concrete frame building (C1M) of High-Code seismic design has Extensive structural damage defined by a median spectral displacement value $(\bar{S}_{d,E})$ of 9.0 inches and a lognormal standard deviation value (β_E) of 0.68. The lognormal fragility curve for Extensive structural damage to this building is shown in Figure 5-5.

In Figure 5-4, the symbol $\bar{S}$ indicates the median value of 9.0 inches. The symbol, S_+, indicates the +1 lognormal standard deviation level of the fragility curve, which is evaluated as $S_+ = \bar{S} * \exp(\beta) = 17.8$ inches.

The corresponding probabilities of being in or exceeding the Extensive damage state for this example are:

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

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

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

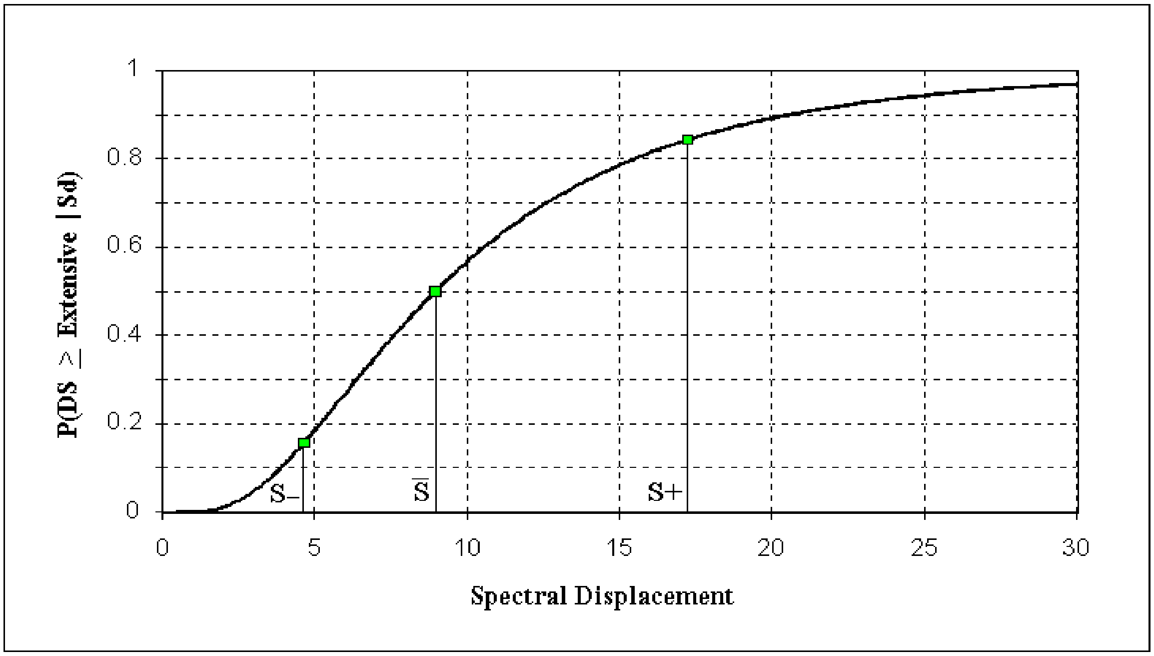


Figure 5-5 Example Fragility Curve - Extensive Structural Damage, C1M Specific Building Type, High-Code Seismic Design

5.4.2.2 Development of Damage State Medians

Median values of fragility curves are developed for each damage state (i.e., Slight, Moderate, Extensive, and Complete) and for each of the three types of building components: structural, nonstructural drift-sensitive, and nonstructural acceleration-sensitive components. Structural fragility is characterized in terms of spectral displacement and by equivalent-PGA fragility curves (for buildings that are components of utility and transportation systems). Section 5.4.3 describes the development of median values of equivalent-PGA structural fragility curves based on the structural fragility curves of this section.

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

Equation 5-4

$$\bar{S}_{d,ds} = \delta_{R,Sds} * \alpha_2 * h$$

Where:

$\bar{S}_{d,ds}$	is the median value of spectral displacement, in inches, of structural components for the damage state, ds
$\delta_{R,Sds}$	is the drift ratio at the threshold of the structural damage state, ds
α_2	is the fraction of the building (roof) height at the location of push-over mode displacement (see Table 5-5)
h	is the typical roof height, in inches, of the specific building type of interest (see Table 5-1)

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

Median values of nonstructural drift-sensitive component fragility are based on building drift ratios that describe the threshold of damage states. Nonstructural drift-sensitive components are identified in Table 5-2. Damage state drift ratios for nonstructural drift-sensitive components are converted to median values of spectral displacement using the same approach as that of Equation 5-4. Values of damage state drift are based, in part, on the work of Ferrito (1982; 1983) and on an update of this data included in a California Division of the State Architect report (DSA, 1996).

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

5.4.2.3 Development of Damage State Variability

Lognormal standard deviation values that describe the variability of fragility curves are developed for each damage state (i.e., Slight, Moderate, Extensive and Complete) and for each of the three types of building components: structural, nonstructural drift-sensitive, and nonstructural acceleration-sensitive components. Structural fragility is characterized in terms of spectral displacement and by equivalent-PGA fragility curves (for buildings that are components of utility and transportation systems). Section 5.4.3 describes the development of variability values for equivalent-PGA structural fragility curves.

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

Equation 5-5

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

Where:

β_{Sds}	is the lognormal standard deviation that describes the total variability for structural damage state, ds,
β_C	is the lognormal standard deviation parameter that describes the variability of the capacity curve,
β_D	is the lognormal standard deviation parameter that describes the variability of the demand spectrum,
$\bar{S}_{d,ds}$	is the median value of spectral displacement, in inches, of structural components for damage state, ds, and

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

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

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

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

Alternate betas have been developed based on calibration specifically for use with USGS ShakeMaps for actual earthquakes; these betas have been reduced to reflect the reduction in ground motion uncertainty associated with ShakeMaps that are based on recorded ground motions (Kircher, 2002). Due to the large number of modified parameters, their values are not reproduced in this section. To review the modified parameters, the user can access them via the Hazus software.

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

5.4.2.4 Structural Damage

Structural damage fragility curves for buildings are described by median values of drift that define the thresholds of the Slight, Moderate, Extensive, and Complete damage states. In general, these estimates of drift are different for each specific building type (including height) and seismic design level. Table 5-11 summarizes the ranges of drift ratios used to define structural damage for various low-rise building types designed to current High-Code seismic provisions. A complete listing of damage-state drift ratios for all building types and heights are provided for each seismic design level in Table 5-12, Table 5-13, Table 5-14, and Table 5-15, respectively.

Table 5-11 Typical Drift Ratios Used to Define Median Values of Structural Damage

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

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

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

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

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

The total variability of each structural damage state is modeled by the combination of following three contributors to damage variability:

- Uncertainty in the damage state threshold of the structural system: $\beta_{\mathrm{M(Sds)}}$ = 0.4, for all structural damage states and building types
- Variability in capacity (response) properties β_{Sds} of the specific building type/seismic design level of interest: $\beta_{\mathrm{C(Au)}}$ = 0.25 for Code buildings, $\beta_{\mathrm{C(Au)}}$ = 0.30 for Pre-Code buildings, and
- Variability in response due to the spatial variability of ground motion

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

Table 5-12, Table 5-13, Table 5-14, and Table 5-15 summarize median and lognormal standard deviation ( ) values for Slight, Moderate, Extensive, and Complete structural damage states for High-Code, Moderate-Code, Low-Code, and Pre-Code buildings, respectively. Note that for the following tables, shaded boxes indicate types that are not permitted by current seismic codes.

Table 5-12 Structural Fragility Curve Parameters - High-Code Seismic Design Level

Building Properties			Inter-Story Drift at Threshold of Damage State				Spectral Displacement (Inches)							
Type	Height (Inches)						Slight		Moderate		Extensive		Complete	
	Roof	Modal	Slight	Moderate	Extensive	Complete	Median	Beta	Median	Beta	Median	Beta	Median	Beta
W1	168	126	0.0040	0.0120	0.0400	0.1000	0.50	0.80	1.51	0.81	5.04	0.85	12.60	0.97
W2	288	216	0.0040	0.0120	0.0400	0.1000	0.86	0.82	2.59	0.88	8.64	0.90	21.60	0.83
S1L	288	216	0.0060	0.0120	0.0300	0.0800	1.30	0.80	2.59	0.76	6.48	0.69	17.28	0.72
S1M	720	540	0.0040	0.0080	0.0200	0.0533	2.16	0.65	4.32	0.65	10.80	0.67	28.80	0.74
S1H	1872	1123	0.0030	0.0060	0.0150	0.0400	3.37	0.64	6.74	0.64	16.85	0.65	44.93	0.67
S2L	288	216	0.0050	0.0100	0.0300	0.0800	1.08	0.81	2.16	0.89	6.48	0.94	17.28	0.83
S2M	720	540	0.0033	0.0067	0.0200	0.0533	1.80	0.67	3.60	0.67	10.80	0.68	28.80	0.79
S2H	1872	1123	0.0025	0.0050	0.0150	0.0400	2.81	0.63	5.62	0.63	16.85	0.64	44.93	0.71
S3	180	135	0.0040	0.0080	0.0240	0.0700	0.54	0.81	1.08	0.83	3.24	0.91	9.45	0.90
S4L	288	216	0.0040	0.0080	0.0240	0.0700	0.86	0.88	1.73	0.90	5.18	0.98	15.12	0.87
S4M	720	540	0.0027	0.0053	0.0160	0.0467	1.44	0.77	2.88	0.73	8.64	0.71	25.20	0.88
S4H	1872	1123	0.0020	0.0040	0.0120	0.0350	2.25	0.64	4.49	0.66	13.48	0.69	39.31	0.77
S5L*							0.65*	1.12*	1.30*	1.04*	3.24*	0.99*	7.56*	0.95*
S5M*							1.08*	0.77*	2.16*	0.79*	5.40*	0.87*	12.60*	0.99*
S5H*							1.68*	0.70*	3.37*	0.73*	8.42*	0.89*	19.66*	0.97*
C1L	240	180	0.0050	0.0100	0.0300	0.0800	0.90	0.81	1.80	0.84	5.40	0.86	14.40	0.80
C1M	600	450	0.0033	0.0067	0.0200	0.0533	1.50	0.68	3.00	0.67	9.00	0.68	24.00	0.81
C1H	1440	864	0.0025	0.0050	0.0150	0.0400	2.16	0.66	4.32	0.64	12.96	0.67	34.56	0.78
C2L	240	180	0.0040	0.0100	0.0300	0.0800	0.72	0.82	1.80	0.84	5.40	0.93	14.40	0.92
C2M	600	450	0.0027	0.0067	0.0200	0.0533	1.20	0.74	3.00	0.77	9.00	0.68	24.00	0.77
C2H	1440	864	0.0020	0.0050	0.0150	0.0400	1.73	0.68	4.32	0.65	12.96	0.66	34.56	0.76
C3L*							0.54*	1.09*	1.08*	1.07*	2.70*	1.08*	6.30*	0.91*
C3M*							0.90*	0.85*	1.80*	0.83*	4.50*	0.79*	10.50*	0.98*
C3H*							1.30*	0.71*	2.59*	0.74*	6.48*	0.90*	15.12*	0.96*
PC1	180	135	0.0040	0.0080	0.0240	0.0700	0.54	0.76	1.08	0.86	3.24	0.88	9.45	1.00

Building Properties			Inter-Story Drift at Threshold of Damage State				Spectral Displacement (Inches)							
Type	Height (Inches)						Slight		Moderate		Extensive		Complete	
	Roof	Modal	Slight	Moderate	Extensive	Complete	Median	Beta	Median	Beta	Median	Beta	Median	Beta
PC2L	240	180	0.0040	0.0080	0.0240	0.0700	0.72	0.84	1.44	0.88	4.32	0.98	12.60	0.94
PC2M	600	450	0.0027	0.0053	0.0160	0.0467	1.20	0.77	2.40	0.80	7.20	0.70	21.00	0.83
PC2H	1,440	864	0.0020	0.0040	0.0120	0.0350	1.73	0.64	3.46	0.66	10.37	0.68	30.24	0.80
RM1L	240	180	0.0040	0.0080	0.0240	0.0700	0.72	0.84	1.44	0.86	4.32	0.92	12.60	1.01
RM1M	600	450	0.0027	0.0053	0.0160	0.0467	1.20	0.71	2.40	0.80	7.20	0.77	21.00	0.75
RM2L	240	180	0.0040	0.0080	0.0240	0.0700	0.72	0.80	1.44	0.82	4.32	0.91	12.60	0.98
RM2M	600	450	0.0027	0.0053	0.0160	0.0467	1.20	0.71	2.40	0.79	7.20	0.70	21.00	0.73
RM2H	1,440	864	0.0020	0.0040	0.0120	0.0350	1.73	0.67	3.46	0.65	10.37	0.66	30.24	0.72
URML*							0.41*	1.00*	0.81*	1.05*	2.03*	1.09*	4.73*	1.08*
URMM*							0.63*	0.91*	1.26*	0.92*	3.15	0.87	7.35*	0.91*
MH	120	120	0.0040	0.0080	0.0240	0.00700	0.48	0.91	0.96	1.00	2.88	1.03	8.40	0.92

**Shaded boxes and building property types with an asterisk (*) indicate types that are not permitted by current seismic codes.*

Table 5-13 Structural Fragility Curve Parameters – Moderate Code Seismic Design Level

Building Properties			Inter-Story Drift at Threshold of Damage State				Spectral Displacement (Inches)							
Type	Height (Inches)						Slight		Moderate		Extensive		Complete	
	Roof	Modal	Slight	Moderate	Extensive	Complete	Median	Beta	Median	Beta	Median	Beta	Median	Beta
W1	168	126	0.0040	0.0099	0.0306	0.0750	0.50	0.84	1.25	0.86	3.86	0.89	9.45	1.04
W2	288	216	0.0040	0.0099	0.0306	0.0750	0.86	0.89	2.14	0.94	6.62	0.94	16.20	0.92
S1L	288	216	0.0060	0.0104	0.0235	0.0600	1.30	0.80	2.24	0.76	5.08	0.74	12.96	0.87
S1M	720	540	0.0040	0.0069	0.0157	0.0400	2.16	0.65	3.74	0.68	8.46	0.69	21.60	0.87
S1H	1,872	1,123	0.0030	0.0052	0.0118	0.0300	3.37	0.64	5.83	0.64	13.21	0.71	33.70	0.83
S2L	288	216	0.0050	0.0087	0.0233	0.0600	1.08	0.93	1.87	0.92	5.04	0.93	12.96	0.93
S2M	720	540	0.0033	0.0058	0.0156	0.0400	1.80	0.70	3.12	0.69	8.40	0.69	21.60	0.89
S2H	1,872	1,123	0.0025	0.0043	0.0117	0.0300	2.81	0.66	4.87	0.64	13.10	0.69	33.70	0.80

Building Properties			Inter-Story Drift at Threshold of Damage State				Spectral Displacement (Inches)							
Type	Height (Inches)						Slight		Moderate		Extensive		Complete	
	Roof	Modal	Slight	Moderate	Extensive	Complete	Median	Beta	Median	Beta	Median	Beta	Median	Beta
S3	180	135	0.0040	0.0070	0.0187	0.0525	0.54	0.88	0.94	0.93	2.52	0.97	7.09	0.89
S4L	288	216	0.0040	0.0069	0.0187	0.0525	0.86	0.96	1.50	1.00	4.04	1.03	11.34	0.92
S4M	720	540	0.0027	0.0046	0.0125	0.0350	1.44	0.75	2.50	0.72	6.73	0.72	18.90	0.94
S4H	1,872	1,123	0.0020	0.0035	0.0093	0.0262	2.25	0.66	3.90	0.67	10.50	0.70	29.48	0.90
S5L*							0.65*	1.12*	1.30*	1.04*	3.24*	0.99*	7.56*	0.95*
S5M*							1.08*	0.77*	2.16*	0.79*	5.40*	0.87*	12.60*	0.99*
S5H*							1.68*	0.70*	3.37*	0.73*	8.42*	0.89*	19.66*	0.97*
C1L	240	180	0.0050	0.0087	0.0233	0.0600	0.90	0.89	1.56	0.90	4.20	0.90	10.80	0.88
C1M	600	450	0.0033	0.0058	0.0156	0.0400	1.50	0.69	2.60	0.69	7.00	0.69	18.00	0.90
C1H	1,440	864	0.0025	0.0043	0.0117	0.0300	2.16	0.66	3.74	0.67	10.08	0.76	25.92	0.91
C2L	240	180	0.0040	0.0084	0.0232	0.0600	0.72	0.92	1.52	0.97	4.17	1.03	10.80	0.87
C2M	600	450	0.0027	0.0056	0.0154	0.0400	1.20	0.821	2.53	0.77	6.95	0.73	18.00	0.91
C2H	1,440	864	0.0020	0.0042	0.0116	0.0300	1.73	0.66	3.64	0.68	10.00	0.70	25.92	0.87
C3L*							0.54*	1.09*	1.08*	1.07*	2.70*	1.08*	6.30*	0.91*
C3M*							0.90*	0.85*	1.80*	0.83*	4.50*	0.79*	10.50*	0.98*
C3H*							1.30*	0.71*	2.59*	0.74*	6.48*	0.90*	15.12*	0.96*
PC1	180	135	0.0040	0.0070	0.0187	0.0525	0.54	0.89	0.94	0.92	2.52	0.97	7.09	1.04
PC2L	240	180	0.0040	0.0069	0.0187	0.0525	0.72	0.96	1.25	1.00	3.37	1.04	9.45	0.88
PC2M	600	450	0.0027	0.0046	0.0125	0.0350	1.20	0.82	2.08	0.79	5.61	0.75	15.75	0.93
PC2H	1,440	864	0.0020	0.0035	0.0094	0.0263	1.73	0.68	3.00	0.69	8.08	0.77	22.68	0.89
RM1L	240	180	0.0040	0.0069	0.0187	0.0525	0.72	0.96	1.25	1.00	3.37	1.05	9.45	0.94
RM1M	600	450	0.0027	0.0046	0.0125	0.0350	1.20	0.82	2.08	0.82	5.61	0.80	15.75	0.88
RM2L	240	180	0.0040	0.0069	0.0187	0.0525	0.72	0.91	1.25	0.95	3.37	1.02	9.45	0.93
RM2M	600	450	0.0027	0.0046	0.0125	0.0350	1.20	0.80	2.08	0.80	5.61	0.76	15.75	0.88
RM2H	1,440	864	0.0020	0.0035	0.0094	0.0263	1.73	0.68	3.00	0.68	8.08	0.70	22.68	0.86
URML*							0.41*	1.00*	0.81*	1.05*	2.03*	1.09*	4.73*	1.08*

Building Properties			Inter-Story Drift at Threshold of Damage State				Spectral Displacement (Inches)							
Type	Height (Inches)						Slight		Moderate		Extensive		Complete	
	Roof	Modal	Slight	Moderate	Extensive	Complete	Median	Beta	Median	Beta	Median	Beta	Median	Beta
URMM*							0.63*	0.91*	1.26*	0.92*	3.15*	0.87*	7.35*	0.91*
MH	120	120	0.0040	0.0080	0.0240	0.0700	0.48	0.91	0.96	1.00	2.88	1.03	8.40	0.92

**Shaded boxes and building property types with an asterisk (*) indicate types that are not permitted by current seismic codes.*

Table 5-14 Structural Fragility Curve Parameters - Low-Code Seismic Design level

Building Properties			Inter-Story Drift at Threshold of Damage State				Spectral Displacement (Inches)							
Type	Height (Inches)						Slight		Moderate		Extensive		Complete	
	Roof	Modal	Slight	Moderate	Extensive	Complete	Median	Beta	Median	Beta	Median	Beta	Median	Beta
W1	168	126	0.0040	0.0099	0.0306	0.0750	0.50	0.93	1.25	0.97	3.86	1.03	9.45	0.99
W2	288	216	0.0040	0.0099	0.0306	0.0750	0.86	0.97	2.14	0.91	6.62	0.88	16.20	1.00
S1L	288	216	0.0060	0.0096	0.0203	0.0500	1.30	0.78	2.07	0.78	4.38	0.78	10.80	0.96
S1M	720	540	0.0040	0.0064	0.0135	0.0333	2.16	0.68	3.44	0.78	7.30	0.85	18.00	0.98
S1H	1,872	1,123	0.0030	0.0048	0.0101	0.0250	3.37	0.66	5.37	0.70	11.38	0.76	28.08	0.92
S2L	288	216	0.0050	0.0080	0.0200	0.0500	1.08	0.95	1.73	0.90	4.32	0.86	10.80	0.99
S2M	720	540	0.0033	0.0053	0.0133	0.0333	1.80	0.69	2.88	0.73	7.20	0.85	18.00	0.97
S2H	1,872	1,123	0.0025	0.0040	0.0100	0.0250	2.81	0.66	4.49	0.68	11.23	0.74	28.08	0.92
S3	180	135	0.0040	0.0064	0.0161	0.0438	0.54	0.99	0.87	0.99	2.17	1.01	5.91	0.91
S4L	288	216	0.0040	0.0064	0.0161	0.0438	0.86	1.05	1.38	0.98	3.47	0.90	9.45	0.99
S4M	720	540	0.0027	0.0043	0.0107	0.0292	1.44	0.76	2.31	0.78	5.78	0.90	15.75	0.99
S4H	1,872	1123	0.0020	0.0032	0.0080	0.0219	2.25	0.70	3.60	0.74	9.01	0.90	24.57	0.98
S5L*	288*	216*	0.0030*	0.0060*	0.0150*	0.0350*	0.65*	1.12*	1.30*	1.04*	3.24*	0.99*	7.56*	0.95*
S5M*	720*	540*	0.0020*	0.0040*	0.0100*	0.0233*	1.08*	0.77*	2.16*	0.79*	5.40*	0.87*	12.60*	0.99*
S5H*	1,872*	1,123*	0.0015*	0.0030*	0.0075*	0.0175*	1.68*	0.70*	3.37*	0.73*	8.42*	0.89*	19.66*	0.97*
C1L	240	180	0.0050	0.0080	0.0200	0.0500	0.90	0.95	1.44	0.91	3.60	0.85	9.00	0.97
C1M	600	450	0.0033	0.0053	0.0133	0.0333	1.50	0.71	2.40	0.74	6.00	0.86	15.00	0.98

Building Properties			Inter-Story Drift at Threshold of Damage State				Spectral Displacement (Inches)							
Type	Height (Inches)						Slight		Moderate		Extensive		Complete	
	Roof	Modal	Slight	Moderate	Extensive	Complete	Median	Beta	Median	Beta	Median	Beta	Median	Beta
C1H	1440	864	0.0025	0.0040	0.0100	0.0250	2.16	0.70	3.46	0.81	8.64	0.89	21.60	0.97
C2L	240	180	0.0040	0.0076	0.0197	0.0500	0.72	1.04	1.37	1.02	3.55	0.99	9.00	0.95
C2M	600	450	0.0027	0.0051	0.0132	0.0333	1.20	0.83	2.29	0.81	5.92	0.82	15.00	1.00
C2H	1440	864	0.0020	0.0038	0.0099	0.0250	1.73	0.68	3.30	0.73	8.53	0.84	21.60	0.95
C3L*	240*	180*	0.0030*	0.0060*	0.0150*	0.0350*	0.54*	1.09*	1.08*	1.07*	2.70*	1.08*	6.30*	0.91*
C3M*	600*	450*	0.0020*	0.0040*	0.0100*	0.0233*	0.90*	0.85*	1.80*	0.83*	4.50*	0.79*	10.50*	0.98*
C3H*	1,440*	864*	0.0015*	0.0030*	0.0075*	0.0175*	1.30*	0.71*	2.59*	0.74*	6.48*	0.90*	15.12	0.96*
PC1	180	135	0.0040	0.0064	0.0161	0.0438	0.54	1.00	0.87	1.05	2.17	1.12	5.91	0.89
PC2L	240	180	0.0040	0.0064	0.0161	0.0438	0.72	1.08	1.15	1.03	2.89	0.98	7.88	0.96
PC2M	600	450	0.0027	0.0043	0.0107	0.0292	1.20	0.81	1.92	0.79	4.81	0.84	13.12	0.99
PC2H	1,440	864	0.0020	0.0032	0.0080	0.0219	1.73	0.72	2.77	0.75	6.93	0.89	18.90	0.98
RM1L	240	180	0.0040	0.0064	0.0161	0.0438	0.72	1.12	1.15	1.10	2.89	1.10	7.88	0.92
RM1M	600	450	0.0027	0.0043	0.0107	0.0292	1.20	0.87	1.92	0.84	4.81	0.79	13.12	0.96
RM2L	240	180	0.0040	0.0064	0.0161	0.0438	0.72	1.05	1.15	1.07	2.89	1.08	7.88	0.91
RM2M	600	450	0.0027	0.0043	0.0107	0.0292	1.20	0.84	1.92	0.81	4.81	0.77	13.12	0.96
RM2H	1,440	864	0.0020	0.0032	0.0080	0.0219	1.73	0.69	2.77	0.72	6.93	0.87	18.90	0.96
URML*	180*	135*	0.0030*	0.0060*	0.0150*	0.0350*	0.41*	1.00*	0.81*	1.05*	2.03*	1.09*	4.73*	1.08*
URMM*	420*	315*	0.0020*	0.0040*	0.0100*	0.0233*	0.63*	0.91*	1.26*	0.92*	3.15*	0.87*	7.35*	0.91*
MH	120	120	0.0040	0.0080	0.0240	0.0700	0.48	0.91	0.96	1.00	2.88	1.03	8.40	0.92

**Shaded boxes and building property types with an asterisk (*) indicate types that are not permitted by current seismic codes.*

Table 5-15 Structural Fragility Curve Parameters - Pre-Code Seismic Design Level

Building Properties			Inter-Story Drift at Threshold of Damage State				Spectral Displacement (Inches)							
Type	Height (Inches)						Slight		Moderate		Extensive		Complete	
	Roof	Modal	Slight	Moderate	Extensive	Complete	Median	Beta	Median	Beta	Median	Beta	Median	Beta
W1	168	126	0.0032	0.0079	0.0245	0.0600	0.40	1.01	1.00	1.05	3.09	1.07	7.56	1.05
W2	288	216	0.0032	0.0079	0.0245	0.0600	0.69	1.04	1.71	0.96	5.29	0.90	12.96	1.00
S1L	288	216	0.0048	0.0076	0.0162	0.0400	1.04	0.85	1.65	0.83	3.50	0.79	8.64	0.95
S1M	720	540	0.0032	0.0051	0.0108	0.0267	1.73	0.71	2.76	0.76	5.84	0.82	14.40	0.97
S1H	1,872	1,123	0.0024	0.0038	0.0081	0.0200	2.70	0.68	4.30	0.71	9.11	0.85	22.46	0.93
S2L	288	216	0.0040	0.0064	0.0160	0.0400	0.86	1.01	1.38	0.96	3.46	0.88	8.64	0.98
S2M	720	540	0.0027	0.0043	0.0107	0.0267	1.44	0.73	2.30	0.75	5.76	0.79	14.40	0.97
S2H	1,872	1,123	0.0020	0.0032	0.0080	0.0200	2.25	0.71	3.59	0.70	8.99	0.84	22.46	0.91
S3	180	135	0.0032	0.0051	0.0128	0.0350	0.43	1.06	0.69	1.03	1.73	1.07	4.73	0.88
S4L	288	216	0.0032	0.0051	0.0128	0.0350	0.69	1.11	1.11	1.03	2.77	0.99	7.56	0.98
S4M	720	540	0.0021	0.0034	0.0086	0.0233	1.15	0.81	1.85	0.79	4.62	0.94	12.60	1.00
S4H	1,872	1,123	0.0016	0.0026	0.0064	0.0175	1.80	0.73	2.88	0.76	7.21	0.90	19.66	0.96
S5L	288	216	0.0024	0.0048	0.0120	0.0280	0.52	1.20	1.04	1.11	2.59	1.08	6.05	0.95
S5M	720	540	0.0016	0.0032	0.0080	0.0187	0.86	0.85	1.73	0.83	4.32	0.94	10.08	0.99
S5H	1,872	1,123	0.0012	0.0024	0.0060	0.0140	1.35	0.72	2.70	0.75	6.74	0.92	15.72	0.96
C1L	240	180	0.0040	0.0064	0.0160	0.0400	0.72	0.98	1.15	0.94	2.88	0.90	7.20	0.96
C1M	600	450	0.0027	0.0043	0.0107	0.0267	1.20	0.73	1.92	0.77	4.80	0.84	12.00	0.98
C1H	1,440	864	0.0020	0.0032	0.0080	0.0200	1.73	0.71	2.76	0.80	6.91	0.94	17.28	1.01
C2L	240	180	0.0032	0.0061	0.0158	0.0400	0.58	1.12	1.10	1.08	2.84	1.06	7.20	0.93
C2M	600	450	0.0021	0.0041	0.0105	0.0267	0.96	0.86	1.83	0.83	4.74	0.80	12.00	0.98
C2H	1,440	864	0.0016	0.0031	0.0079	0.0200	1.38	0.73	2.64	0.75	6.82	0.92	17.28	0.97
C3L	240	180	0.0024	0.0048	0.0120	0.0280	0.43	1.19	0.86	1.15	2.16	1.16	5.04	0.92
C3M	600	450	0.0016	0.0032	0.0080	0.0187	0.72	0.90	1.44	0.86	3.60	0.90	8.40	0.96

Building Properties			Inter-Story Drift at Threshold of Damage State				Spectral Displacement (Inches)							
Type	Height (Inches)						Slight		Moderate		Extensive		Complete	
	Roof	Modal	Slight	Moderate	Extensive	Complete	Median	Beta	Median	Beta	Median	Beta	Median	Beta
C3H	1,440	864	0.0012	0.0024	0.0060	0.0140	1.04	0.73	2.07	0.74	5.18	0.90	12.10	0.95
PC1	180	135	0.0032	0.0051	0.0128	0.0350	0.43	1.14	0.69	1.14	1.73	1.17	4.73	0.99
PC2L	240	180	0.0032	0.0051	0.0128	0.0350	0.58	1.14	0.92	1.10	2.31	1.10	6.30	0.93
PC2M	600	450	0.0021	0.0034	0.0086	0.0233	0.96	0.87	1.54	0.83	3.85	0.92	10.50	1.00
PC2H	1,440	864	0.0016	0.0026	0.0064	0.0175	1.38	0.74	2.21	0.76	5.55	0.91	15.12	0.96
RM1L	240	180	0.0032	0.0051	0.0128	0.0350	0.58	1.20	0.92	1.17	2.31	1.17	6.30	0.94
RM1M	600	450	0.0021	0.0034	0.0086	0.0233	0.96	0.92	1.54	0.89	3.85	0.88	10.50	0.96
RM2L	240	180	0.0032	0.0051	0.0128	0.0350	0.58	1.14	0.92	1.10	2.31	1.15	6.30	0.92
RM2M	600	450	0.0021	0.0034	0.0086	0.0233	0.96	0.90	1.54	0.87	3.85	0.86	10.50	0.96
RM2H	1,440	864	0.0016	0.0026	0.0064	0.0175	1.38	0.75	2.21	0.75	5.55	0.85	15.12	0.94
URML	180	135	0.0024	0.0048	0.0120	0.0280	0.32	1.15	0.65	1.19	1.62	1.20	3.78	1.18
URMM	420	315	0.0016	0.0032	0.0080	0.0187	0.50	1.0	1.01	0.97	2.52	0.90	5.88	0.88
MH	120	120	0.0032	0.0064	0.0192	0.0560	0.38	1.12	0.77	1.10	2.30	0.95	6.72	0.97

5.4.2.5 Nonstructural Damage - Drift-Sensitive Components

Table 5-16 summarizes drift ratios used by the methodology to define the median values of damage fragility curves for drift-sensitive nonstructural components of buildings. Nonstructural damage drift ratios are assumed to be the same for each building type and each seismic design level.

Table 5-16 Drift Ratios Used to Define Median Values of Damage for Nonstructural Drift-Sensitive Components

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

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

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

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

Each of these three contributors to damage state variability is assumed to be lognormally distributed random variables. Capacity and demand are dependent parameters and a convolution process is used to derive combined capacity/demand variability of each nonstructural damage state. Capacity/demand variability is then combined with damage state uncertainty as described in Section 5.4.2.3.

Table 5-17, Table 5-18, Table 5-19, and Table 5-20 summarize median and lognormal standard deviation (β_{NSDds}) values for Slight, Moderate, Extensive, and Complete nonstructural drift-sensitive damage states for High-Code, Moderate-Code, Low-Code, and Pre-Code buildings, respectively. Median values are the same for all design levels. Lognormal standard deviation values are slightly different for each seismic design level. Note that for the following tables, shaded boxes indicate types that are not permitted by current seismic codes.

Table 5-17 Nonstructural Drift-Sensitive Fragility Curve Parameters High-Code Seismic Design Level

Building Type	Median Spectral Displacement (inches) and Logstandard Deviation (Beta)							
	Slight		Moderate		Extensive		Complete	
	Median	Beta	Median	Beta	Median	Beta	Median	Beta
W1	0.50	0.85	1.01	0.88	3.15	0.87	6.30	0.94
W2	0.86	0.87	1.73	0.89	5.40	0.96	10.80	0.94
S1L	0.86	0.81	1.73	0.85	5.40	0.77	10.80	0.76
S1M	2.16	0.72	4.32	0.72	13.50	0.72	27.00	0.80
S1H	4.49	0.72	8.99	0.71	28.08	0.74	56.16	0.77
S2L	0.86	0.84	1.73	0.90	5.40	0.97	10.80	0.92
S2M	2.16	0.72	4.32	0.74	13.50	0.75	27.00	0.83
S2H	4.49	0.71	8.99	0.71	28.08	0.72	56.16	0.78
S3	0.54	0.86	1.08	0.88	3.38	0.98	6.75	0.98
S4L	0.86	0.93	1.73	0.95	5.40	1.01	10.80	1.00
S4M	2.16	0.80	4.32	0.75	13.50	0.76	27.00	0.94
S4H	4.49	0.72	8.99	0.72	28.08	0.79	56.16	0.91
S5L*	0.86*	1.14*	1.73*	1.04*	5.40*	0.98*	10.80*	1.01*
S5M*	2.16*	0.84*	4.32*	0.95*	13.50*	1.03*	27.00*	1.08*
S5H*	4.49*	0.84*	8.99*	0.96*	28.08*	1.03*	56.16*	1.06*
C1L	0.72	0.85	1.44	0.88	4.50	0.90	9.00	0.89
C1M	1.80	0.72	3.60	0.73	11.25	0.75	22.50	0.85
C1H	3.46	0.71	6.91	0.71	21.60	0.78	43.20	0.89
C2L	0.72	0.87	1.44	0.87	4.50	0.97	9.00	0.99
C2M	1.80	0.83	3.60	0.82	11.25	0.74	22.50	0.81
C2H	3.46	0.70	6.91	0.72	21.60	0.74	43.20	0.85
C3L*	0.72*	1.13*	1.44*	1.08*	4.50*	0.95*	9.00*	1.00*
C3M*	1.80*	0.88*	3.60*	0.92*	11.25*	1.01*	22.50*	1.06*
C3H*	3.46*	0.83*	6.91*	0.96*	21.60*	1.02*	43.20*	1.05*
PC1	0.54	0.82	1.08	0.91	3.38	0.95	6.75	1.03
PC2L	0.72	0.90	1.44	0.93	4.50	1.03	9.00	1.04
PC2M	1.80	0.87	3.60	0.83	11.25	0.76	22.50	0.90
PC2H	3.46	0.73	6.91	0.73	21.60	0.77	43.20	0.89
RM1L	0.72	0.89	1.44	0.91	4.50	0.97	9.00	1.06
RM1M	1.80	0.82	3.60	0.86	11.25	0.80	22.50	0.81
RM2L	0.72	0.85	1.44	0.87	4.50	0.95	9.00	1.03
RM2M	1.80	0.82	3.60	0.84	11.25	0.76	22.50	0.80
RM2H	3.46	0.71	6.91	0.73	21.60	0.73	43.20	0.85
URML*	0.54*	1.07*	1.08*	1.12*	3.38*	1.17*	6.75*	1.01*
URMM*	1.26*	0.97*	2.52*	0.91*	7.88*	0.98*	15.75*	1.04*
MH	0.48	0.96	0.96	1.05	3.00	1.08	6.00	0.93

**Shaded boxes and building types with an asterisk (*) indicate types that are not permitted by current seismic codes.*

Table 5-18 Nonstructural Drift-Sensitive Fragility Curve Parameters - Moderate-Code Seismic Design Level

Building Type	Median Spectral Displacement (inches) and Logstandard Deviation (Beta)							
	Slight		Moderate		Extensive		Complete	
	Median	Beta	Median	Beta	Median	Beta	Median	Beta
W1	0.50	0.89	1.01	0.91	3.15	0.90	6.30	1.04
W2	0.86	0.94	1.73	0.98	5.40	1.00	10.80	0.90
S1L	0.86	0.85	1.73	0.83	5.40	0.79	10.80	0.87
S1M	2.16	0.72	4.32	0.74	13.50	0.85	27.00	0.95
S1H	4.49	0.71	8.99	0.73	28.08	0.84	56.16	0.95
S2L	0.86	0.93	1.73	0.98	5.40	0.96	10.80	0.92
S2M	2.16	0.74	4.32	0.74	13.50	0.85	27.00	0.96
S2H	4.49	0.72	8.99	0.73	28.08	0.81	56.16	0.94
S3	0.54	0.93	1.08	0.98	3.38	1.01	6.75	0.94
S4L	0.86	1.00	1.73	1.05	5.40	1.00	10.80	0.96
S4M	2.16	0.78	4.32	0.80	13.50	0.95	27.00	1.04
S4H	4.49	0.73	8.99	0.82	28.08	0.93	56.16	1.01
S5L*	0.86*	1.14*	1.73*	1.04*	5.40*	0.98*	10.80*	1.01*
S5M*	2.16*	0.84*	4.32*	0.95*	13.50*	1.03*	27.00*	1.08*
S5H*	4.49*	0.84*	8.99*	0.96*	28.08*	1.03*	56.16*	1.06*
C1L	0.72	0.92	1.44	0.96	4.50	0.95	9.00	0.89
C1M	1.80	0.76	3.60	0.76	11.25	0.87	22.50	0.98
C1H	3.46	0.74	6.91	0.81	21.60	0.95	43.20	1.03
C2L	0.72	0.96	1.44	1.00	4.50	1.06	9.00	0.95
C2M	1.80	0.83	3.60	0.81	11.25	0.83	22.50	0.97
C2H	3.46	0.73	6.91	0.76	21.60	0.89	43.20	1.00
C3L*	0.72*	1.13*	1.44*	1.08*	4.50*	0.95*	9.00*	1.00*
C3M*	1.80*	0.88*	3.60*	0.92*	11.25*	1.01*	22.50*	1.06*
C3H*	3.46*	0.83*	6.91*	0.96*	21.60*	1.02*	43.20*	1.05*
PC1	0.54	0.94	1.08	0.99	3.38	1.05	6.75	1.08
PC2L	0.72	1.00	1.44	1.06	4.50	1.07	9.00	0.92
PC2M	1.80	0.86	3.60	0.83	11.25	0.92	22.50	1.00
PC2H	3.46	0.74	6.91	0.79	21.60	0.93	43.20	1.02
RM1L	0.72	1.01	1.44	1.06	4.50	1.11	9.00	1.01
RM1M	1.80	0.89	3.60	0.85	11.25	0.84	22.50	0.98
RM2L	0.72	0.96	1.44	1.02	4.50	1.10	9.00	0.99
RM2M	1.80	0.87	3.60	0.83	11.25	0.82	22.50	0.98
RM2H	3.46	0.73	6.91	0.76	21.60	0.88	43.20	0.99
URML*	0.54	1.07	1.08	1.12	3.38	1.17	6.75	1.01
URMM*	1.26	0.97	2.52	0.91	7.88	0.98	15.75	1.04
MH	0.48	0.96	0.96	1.05	3.00	1.08	6.00	0.93

**Shaded boxes and building types with an asterisk (*) indicate types that are not permitted by current seismic codes.*

Table 5-19 Nonstructural Drift-Sensitive Fragility Curve Parameters Low-Code Seismic Design Level

Building Type	Median Spectral Displacement (inches) and Logstandard Deviation (Beta)							
	Slight		Moderate		Extensive		Complete	
	Median	Beta	Median	Beta	Median	Beta	Median	Beta
W1	0.50	0.98	1.01	1.00	3.15	1.02	6.30	1.09
W2	0.86	1.01	1.73	0.97	5.40	0.93	10.80	1.03
S1L	0.86	0.86	1.73	0.84	5.40	0.88	10.80	1.00
S1M	2.16	0.75	4.32	0.89	13.50	0.99	27.00	1.05
S1H	4.49	0.75	8.99	0.87	28.08	0.97	56.16	1.04
S2L	0.86	1.01	1.73	0.95	5.40	0.94	10.80	1.03
S2M	2.16	0.77	4.32	0.87	13.50	0.99	27.00	1.05
S2H	4.49	0.74	8.99	0.86	28.08	0.97	56.16	1.04
S3	0.54	1.03	1.08	1.02	3.38	0.96	6.75	0.99
S4L	0.86	1.09	1.73	0.99	5.40	0.96	10.80	1.03
S4M	2.16	0.82	4.32	0.96	13.50	1.04	27.00	1.08
S4H	4.49	0.84	8.99	0.95	28.08	1.05	56.16	1.07
S5L	0.86	1.14	1.73	1.04	5.40	0.98	10.80	1.01
S5M	2.16	0.84	4.32	0.95	13.50	1.03	27.00	1.08
S5H	4.49	0.84	8.99	0.96	28.08	1.03	56.16	1.06
C1L	0.72	1.00	1.44	0.96	4.50	0.90	9.00	1.02
C1M	1.80	0.79	3.60	0.88	11.25	0.99	22.50	1.06
C1H	3.46	0.87	6.91	0.96	21.60	1.02	43.20	1.07
C2L	0.72	1.08	1.44	1.05	4.50	0.95	9.00	1.00
C2M	1.80	0.83	3.60	0.87	11.25	1.00	22.50	1.06
C2H	3.46	0.79	6.91	0.92	21.60	1.00	43.20	1.07
C3L	0.72	1.13	1.44	1.08	4.50	0.95	9.00	1.00
C3M	1.80	0.88	3.60	0.92	11.25	1.01	22.50	1.06
C3H	3.46	0.83	6.91	0.96	21.60	1.02	43.20	1.05
PC1	0.54	1.04	1.08	1.10	3.38	1.10	6.75	0.94
PC2L	0.72	1.12	1.44	1.04	4.50	0.93	9.00	1.02
PC2M	1.80	0.86	3.60	0.94	11.25	1.02	22.50	1.07
PC2H	3.46	0.83	6.91	0.94	21.60	1.04	43.20	1.07
RM1L	0.72	1.16	1.44	1.12	4.50	1.03	9.00	0.99
RM1M	1.80	0.89	3.60	0.89	11.25	1.00	22.50	1.05
RM2L	0.72	1.09	1.44	1.08	4.50	1.01	9.00	0.99
RM2M	1.80	0.85	3.60	0.86	11.25	1.00	22.50	1.06
RM2H	3.46	0.79	6.91	0.92	21.60	0.98	43.20	1.07
URML	0.54	1.07	1.08	1.12	3.38	1.17	6.75	1.01
URMM	1.26	0.97	2.52	0.91	7.88	0.98	15.75	1.04
MH	0.48	0.96	0.96	1.05	3.00	1.08	6.00	0.93

Table 5-20 Nonstructural Drift-Sensitive Fragility Curve Parameters - Pre-Code Seismic Design Level

Building Type	Median Spectral Displacement (inches) and Logstandard Deviation (Beta)							
	Slight		Moderate		Extensive		Complete	
	Median	Beta	Median	Beta	Median	Beta	Median	Beta
W1	0.50	1.07	1.01	1.11	3.15	1.11	6.30	1.15
W2	0.86	1.06	1.73	1.00	5.40	0.93	10.80	1.01
S1L	0.86	0.90	1.73	0.87	5.40	0.91	10.80	1.02
S1M	2.16	0.80	4.32	0.92	13.50	1.00	27.00	1.06
S1H	4.49	0.79	8.99	0.89	28.08	1.00	56.16	1.07
S2L	0.86	1.05	1.73	0.97	5.40	0.96	10.80	1.04
S2M	2.16	0.79	4.32	0.90	13.50	1.02	27.00	1.07
S2H	4.49	0.79	8.99	0. 90	28.08	0.99	56.16	1.05
S3	0.54	1.11	1.08	1.05	3.38	0.96	6.75	1.00
S4L	0.86	1.12	1.73	1.01	5.40	0.99	10.80	1.05
S4M	2.16	0.86	4.32	0.98	13.50	1.05	27.00	1.10
S4H	4.49	0.88	8.99	0.99	28.08	1.07	56.16	1.09
S5L	0.86	1.18	1.73	1.06	5.40	0.98	10.80	1.03
S5M	2.16	0.86	4.32	0.99	13.50	1.05	27.00	1.09
S5H	4.49	0.87	8.99	0.91	28.08	1.05	56.16	1.09
C1L	0.72	1.02	1.44	0.98	4.50	0.93	9.00	1.03
C1M	1.80	0.82	3.60	0.91	11.25	1.02	22.50	1.06
C1H	3.46	0.90	6.91	0.99	21.60	1.05	43.20	1.10
C2L	0.72	1.15	1.44	1.08	4.50	0.97	9.00	1.01
C2M	1.80	0.89	3.60	0.90	11.25	1.03	22.50	1.07
C2H	3.46	0.83	6.91	0.96	21.60	1.04	43.20	1.08
C3L	0.72	1.19	1.44	1.11	4.50	0.99	9.00	1.02
C3M	1.80	0.91	3.60	0.95	11.25	1.03	22.50	1.09
C3H	3.46	0.86	6.91	0.90	21.60	1.04	43.20	1.09
PC1	0.54	1.18	1.08	1.16	3.38	1.12	6.75	0.95
PC2L	0.72	1.16	1.44	1.06	4.50	0.96	9.00	1.02
PC2M	1.80	0.87	3.60	0.96	11.25	1.04	22.50	1.08
PC2H	3.46	0.87	6.91	0.98	21.60	1.06	43.20	1.08
RM1L	0.72	1.22	1.44	1.14	4.50	1.03	9.00	1.00
RM1M	1.80	0.93	3.60	0.92	11.25	1.02	22.50	1.07
RM2L	0.72	1.17	1.44	1.12	4.50	1.01	9.00	0.99
RM2M	1.80	0.90	3.60	0.90	11.25	1.01	22.50	1.07
RM2H	3.46	0.82	6.91	0.96	21.60	1.04	43.20	1.08
URML	0.54	1.21	1.08	1.22	3.38	1.22	6.75	1.03
URMM	1.26	0.99	2.52	0.95	7.88	1.00	15.75	1.05
MH	0.48	1.15	0.96	1.09	3.00	0.94	6.00	0.99

5.4.2.6 Nonstructural Damage – Acceleration-Sensitive Components

Table 5-21 summarizes the peak floor acceleration values used by the methodology to define the median values of fragility curves for acceleration-sensitive nonstructural components of buildings. Nonstructural damage acceleration values are assumed to be the same for each specific building type, but to vary by seismic design level.

Table 5-21 Peak Floor Accelerations Used to Define Median Values of Damage to Nonstructural Acceleration-Sensitive Components

Seismic Design Level	Floor Acceleration at the Threshold of Nonstructural Data (g)			
	Slight	Moderate	Extensive	Complete
High-Code	0.30	0.60	1.20	2.40
Moderate-Code	0.25	0.50	1.00	2.00
Low-Code	0.20	0.40	0.80	1.60
Pre-Code	0.20	0.40	0.80	1.60

The floor acceleration values are used directly as median values, assuming average upper-floor demand is represented by response at the point of the push-over mode displacement.

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

- Uncertainty in the damage-state threshold of nonstructural components: $\beta_{M(NSAds)}$ = 0.6, for all damage states and building types
- Variability in capacity (response) properties of the specific building type that contains the nonstructural components of interest: $\beta_{C(Au)}$ = 0.25 for Code buildings, $\beta_{C(Au)}$ = 0.30 for Pre-Code buildings
- Variability in response of the specific building type due to the spatial variability of ground motion demand: $\beta_{D(A)}$= 0.45 and $\beta_{C(V)}$ = 0.50

Each of these three contributors to damage state variability is assumed to be lognormally distributed random variables. Capacity and demand are dependent parameters and a convolution process is used to derive combined capacity/demand variability of each nonstructural damage state. Capacity/demand variability is then combined with damage state uncertainty as described in Section 5.4.2.3.

Table 5-22, Table 5-23, Table 5-24, and Table 5-25 summarize median and lognormal standard deviation (β_{NSAds}) values for Slight, Moderate, Extensive, and Complete nonstructural acceleration-sensitive damage states for High-Code, Moderate-Code, Low-Code, and Pre-Code buildings, respectively. Median values are the same for all building types, except for MH (manufactured housing), which utilize the Moderate-Code Design Level floor accelerations as median values for all Design Levels. Lognormal standard deviation values are slightly different for each building type. Note that for the following tables, shaded boxes indicate types that are not permitted by current seismic codes.

Table 5-22 Nonstructural Acceleration-Sensitive Fragility Curve Parameters - High-Code Seismic Design Level

Building Type	Median Spectral Acceleration (g) and Logstandard Deviation (Beta)							
	Slight		Moderate		Extensive		Complete	
	Median	Beta	Median	Beta	Median	Beta	Median	Beta
W1	0.30	0.73	0.60	0.69	1.20	0.68	2.40	0.67
W2	0.30	0.71	0.60	0.67	1.20	0.67	2.40	0.68
S1L	0.30	0.67	0.60	0.67	1.20	0.67	2.40	0.66
S1M	0.30	0.67	0.60	0.68	1.20	0.67	2.40	0.67
S1H	0.30	0.69	0.60	0.67	1.20	0.67	2.40	0.67
S2L	0.30	0.67	0.60	0.66	1.20	0.67	2.40	0.67
S2M	0.30	0.69	0.60	0.66	1.20	0.66	2.40	0.66
S2H	0.30	0.68	0.60	0.66	1.20	0.65	2.40	0.65
S3	0.30	0.68	0.60	0.67	1.20	0.66	2.40	0.66
S4L	0.30	0.68	0.60	0.68	1.20	0.67	2.40	0.67
S4M	0.30	0.67	0.60	0.65	1.20	0.66	2.40	0.66
S4H	0.30	0.67	0.60	0.66	1.20	0.65	2.40	0.65
S5L*	0.20*	0.65*	0.40*	0.68*	0.80*	0.67*	1.60*	0.67*
S5M*	0.20*	0.64*	0.40*	0.67*	0.80*	0.66*	1.60*	0.66*
S5H*	0.20*	0.65*	0.40*	0.68*	0.80*	0.68*	1.60*	0.68*
C1L	0.30	0.67	0.60	0.68	1.20	0.67	2.40	0.67
C1M	0.30	0.67	0.60	0.67	1.20	0.66	2.40	0.66
C1H	0.30	0.66	0.60	0.66	1.20	0.66	2.40	0.66
C2L	0.30	0.70	0.60	0.67	1.20	0.66	2.40	0.64
C2M	0.30	0.70	0.60	0.66	1.20	0.65	2.40	0.65
C2H	0.30	0.68	0.60	0.66	1.20	0.65	2.40	0.65
C3L*	0.20*	0.65*	0.40*	0.67*	0.80*	0.66*	1.60*	0.66*
C3M*	0.20*	0.64*	0.40*	0.67*	0.80*	0.66*	1.60*	0.66*
C3H*	0.20*	0.64*	0.40*	0.67*	0.80*	0.67*	1.60*	0.67*
PC1	0.30	0.74	0.60	0.67	1.20	0.67	2.40	0.64
PC2L	0.30	0.69	0.60	0.67	1.20	0.67	2.40	0.67
PC2M	0.30	0.68	0.60	0.65	1.20	0.66	2.40	0.66
PC2H	0.30	0.67	0.60	0.65	1.20	0.65	2.40	0.65
RM1L	0.30	0.71	0.60	0.67	1.20	0.67	2.40	0.63
RM1M	0.30	0.72	0.60	0.66	1.20	0.65	2.40	0.65
RM2L	0.30	0.71	0.60	0.66	1.20	0.67	2.40	0.64
RM2M	0.30	0.72	0.60	0.65	1.20	0.65	2.40	0.65
RM2H	0.30	0.70	0.60	0.65	1.20	0.65	2.40	0.65
URML*	0.20*	0.69*	0.40*	0.66*	0.80*	0.65*	1.60*	0.65*
URMM*	0.20*	0.64*	0.40*	0.66*	0.80*	0.66*	1.60*	0.66*
MH	0.25	0.65	0.50	0.67	1.00	0.67	2.00	0.67

**Shaded boxes and building types with an asterisk (*) indicate types that are not permitted by current seismic codes.*

Table 5-23 Nonstructural Acceleration-Sensitive Fragility Curve Parameters - Moderate-Code Seismic Design Level

Building Type	Median Spectral Acceleration (g) and Logstandard Deviation (Beta)							
	Slight		Moderate		Extensive		Complete	
	Median	Beta	Median	Beta	Median	Beta	Median	Beta
W1	0.25	0.72	0.50	0.68	1.00	0.67	2.00	0.64
W2	0.25	0.68	0.50	0.66	1.00	0.68	2.00	0.68
S1L	0.25	0.67	0.50	0.66	1.00	0.67	2.00	0.67
S1M	0.25	0.66	0.50	0.67	1.00	0.67	2.00	0.67
S1H	0.25	0.66	0.50	0.67	1.00	0.67	2.00	0.67
S2L	0.25	0.66	0.50	0.66	1.00	0.68	2.00	0.68
S2M	0.25	0.66	0.50	0.65	1.00	0.66	2.00	0.66
S2H	0.25	0.66	0.50	0.66	1.00	0.66	2.00	0.66
S3	0.25	0.67	0.50	0.66	1.00	0.65	2.00	0.65
S4L	0.25	0.66	0.50	0.66	1.00	0.66	2.00	0.66
S4M	0.25	0.65	0.50	0.66	1.00	0.65	2.00	0.65
S4H	0.25	0.65	0.50	0.66	1.00	0.66	2.00	0.66
S5L*	0.20*	0.65*	0.40*	0.68*	0.80*	0.67*	1.60*	0.67*
S5M*	0.20*	0.64*	0.40*	0.67*	0.80*	0.66*	1.60*	0.66*
S5H*	0.20*	0.65*	0.40*	0.68*	0.80*	0.68*	1.60*	0.68*
C1L	0.25	0.67	0.50	0.66	1.00	0.66	2.00	0.66
C1M	0.25	0.66	0.50	0.66	1.00	0.63	2.00	0.63
C1H	0.25	0.65	0.50	0.67	1.00	0.67	2.00	0.67
C2L	0.25	0.68	0.50	0.66	1.00	0.67	2.00	0.67
C2M	0.25	0.67	0.50	0.64	1.00	0.66	2.00	0.66
C2H	0.25	0.66	0.50	0.65	1.00	0.65	2.00	0.65
C3L*	0.20*	0.65*	0.40*	0.67*	0.80*	0.66*	1.60*	0.66*
C3M*	0.20*	0.64*	0.40*	0.67*	0.80*	0.66*	1.60*	0.66*
C3H*	0.20*	0.64*	0.40*	0.67*	0.80*	0.67*	1.60*	0.67*
PC1	0.25	0.68	0.50	0.67	1.00	0.66	2.00	0.66
PC2L	0.25	0.66	0.50	0.66	1.00	0.65	2.00	0.65
PC2M	0.25	0.65	0.50	0.65	1.00	0.65	2.00	0.65
PC2H	0.25	0.64	0.50	0.65	1.00	0.65	2.00	0.65
RM1L	0.25	0.69	0.50	0.67	1.00	0.67	2.00	0.67
RM1M	0.25	0.67	0.50	0.64	1.00	0.67	2.00	0.67
RM2L	0.25	0.68	0.50	0.66	1.00	0.67	2.00	0.67
RM2M	0.25	0.67	0.50	0.64	1.00	0.67	2.00	0.67
RM2H	0.25	0.66	0.50	0.64	1.00	0.64	2.00	0.64
URML*	0.20*	0.69*	0.40*	0.66*	0.80*	0.65*	1.60*	0.65*
URMM*	0.20*	0.64*	0.40*	0.66*	0.80*	0.66*	1.60*	0.66*
MH	0.25	0.65	0.50	0.67	1.00	0.67	2.00	0.67

**Shaded boxes and building types with an asterisk (*) indicate types that are not permitted by current seismic codes.*

Table 5-24 Nonstructural Acceleration-Sensitive Fragility Curve Parameters - Low-Code Seismic Design Level

Building Type	Median Spectral Acceleration (g) and Logstandard Deviation (Beta)							
	Slight		Moderate		Extensive		Complete	
	Median	Beta	Median	Beta	Median	Beta	Median	Beta
W1	0.20	0.71	0.40	0.68	0.80	0.66	1.60	0.66
W2	0.20	0.67	0.40	0.67	0.80	0.70	1.60	0.70
S1L	0.20	0.65	0.40	0.68	0.80	0.68	1.60	0.68
S1M	0.20	0.66	0.40	0.69	0.80	0.69	1.60	0.69
S1H	0.20	0.67	0.40	0.65	0.80	0.65	1.60	0.65
S2L	0.20	0.65	0.40	0.68	0.80	0.68	1.60	0.68
S2M	0.20	0.64	0.40	0.67	0.80	0.67	1.60	0.67
S2H	0.20	0.65	0.40	0.68	0.80	0.68	1.60	0.68
S3	0.20	0.65	0.40	0.68	0.80	0.68	1.60	0.68
S4L	0.20	0.65	0.40	0.68	0.80	0.68	1.60	0.68
S4M	0.20	0.65	0.40	0.68	0.80	0.68	1.60	0.68
S4H	0.20	0.65	0.40	0.68	0.80	0.68	1.60	0.68
S5L	0.20	0.65	0.40	0.68	0.80	0.67	1.60	0.67
S5M	0.20	0.64	0.40	0.67	0.80	0.66	1.60	0.66
S5H	0.20	0.65	0.40	0.68	0.80	0.68	1.60	0.68
C1L	0.20	0.65	0.40	0.68	0.80	0.68	1.60	0.68
C1M	0.20	0.65	0.40	0.68	0.80	0.68	1.60	0.68
C1H	0.20	0.67	0.40	0.67	0.80	0.67	1.60	0.67
C2L	0.20	0.66	0.40	0.67	0.80	0.66	1.60	0.66
C2M	0.20	0.63	0.40	0.66	0.80	0.65	1.60	0.65
C2H	0.20	0.64	0.40	0.66	0.80	0.66	1.60	0.66
C3L	0.20	0.65	0.40	0.67	0.80	0.66	1.60	0.66
C3M	0.20	0.64	0.40	0.67	0.80	0.66	1.60	0.66
C3H	0.20	0.64	0.40	0.67	0.80	0.67	1.60	0.67
PC1	0.20	0.66	0.40	0.66	0.80	0.66	1.60	0.66
PC2L	0.20	0.65	0.40	0.68	0.80	0.68	1.60	0.68
PC2M	0.20	0.64	0.40	0.67	0.80	0.67	1.60	0.67
PC2H	0.20	0.64	0.40	0.67	0.80	0.67	1.60	0.67
RM1L	0.20	0.66	0.40	0.66	0.80	0.64	1.60	0.64
RM1M	0.20	0.64	0.40	0.66	0.80	0.64	1.60	0.64
RM2L	0.20	0.66	0.40	0.66	0.80	0.64	1.60	0.64
RM2M	0.20	0.64	0.40	0.66	0.80	0.65	1.60	0.65
RM2H	0.20	0.63	0.40	0.66	0.80	0.66	1.60	0.66
URML	0.20	0.69	0.40	0.66	0.80	0.65	1.60	0.65
URMM	0.20	0.64	0.40	0.66	0.80	0.66	1.60	0.66
MH	0.25	0.65	0.50	0.67	1.00	0.67	2.00	0.67

Table 5-25 Nonstructural Acceleration-Sensitive Fragility Curve Parameters - Pre-Code Seismic Design Level

Building Type	Median Spectral Acceleration (g) and Logstandard Deviation (Beta)							
	Slight		Moderate		Extensive		Complete	
	Median	Beta	Median	Beta	Median	Beta	Median	Beta
W1	0.20	0.72	0.40	0.70	0.80	0.66	1.60	0.66
W2	0.20	0.66	0.40	0.67	0.80	0.65	1.60	0.65
S1L	0.20	0.66	0.40	0.68	0.80	0.68	1.60	0.68
S1M	0.20	0.66	0.40	0.69	0.80	0.69	1.60	0.69
S1H	0.20	0.67	0.40	0.67	0.80	0.67	1.60	0.67
S2L	0.20	0.65	0.40	0.68	0.80	0.68	1.60	0.68
S2M	0.20	0.65	0.40	0.68	0.80	0.68	1.60	0.68
S2H	0.20	0.66	0.40	0.67	0.80	0.67	1.60	0.67
S3	0.20	0.65	0.40	0.68	0.80	0.68	1.60	0.68
S4L	0.20	0.66	0.40	0.68	0.80	0.68	1.60	0.68
S4M	0.20	0.65	0.40	0.68	0.80	0.68	1.60	0.68
S4H	0.20	0.66	0.40	0.67	0.80	0.67	1.60	0.67
S5L	0.20	0.65	0.40	0.68	0.80	0.68	1.60	0.68
S5M	0.20	0.65	0.40	0.68	0.80	0.68	1.60	0.68
S5H	0.20	0.66	0.40	0.68	0.80	0.68	1.60	0.68
C1L	0.20	0.66	0.40	0.68	0.80	0.68	1.60	0.68
C1M	0.20	0.66	0.40	0.68	0.80	0.68	1.60	0.68
C1H	0.20	0.67	0.40	0.67	0.80	0.67	1.60	0.67
C2L	0.20	0.65	0.40	0.67	0.80	0.67	1.60	0.67
C2M	0.20	0.64	0.40	0.67	0.80	0.67	1.60	0.67
C2H	0.20	0.65	0.40	0.67	0.80	0.67	1.60	0.67
C3L	0.20	0.65	0.40	0.68	0.80	0.68	1.60	0.68
C3M	0.20	0.64	0.40	0.67	0.80	0.67	1.60	0.67
C3H	0.20	0.65	0.40	0.67	0.80	0.67	1.60	0.67
PC1	0.20	0.66	0.40	0.66	0.80	0.66	1.60	0.66
PC2L	0.20	0.65	0.40	0.68	0.80	0.68	1.60	0.68
PC2M	0.20	0.65	0.40	0.67	0.80	0.67	1.60	0.67
PC2H	0.20	0.66	0.40	0.66	0.80	0.66	1.60	0.66
RM1L	0.20	0.66	0.40	0.67	0.80	0.66	1.60	0.66
RM1M	0.20	0.64	0.40	0.66	0.80	0.65	1.60	0.65
RM2L	0.20	0.66	0.40	0.67	0.80	0.67	1.60	0.67
RM2M	0.20	0.64	0.40	0.66	0.80	0.66	1.60	0.66
RM2H	0.20	0.65	0.40	0.66	0.80	0.66	1.60	0.66
URML	0.20	0.69	0.40	0.65	0.80	0.65	1.60	0.65
URMM	0.20	0.64	0.40	0.66	0.80	0.66	1.60	0.66
MH	0.25	0.67	0.50	0.65	1.00	0.65	2.00	0.65

5.4.3 Structural Fragility Curves - Equivalent Peak Ground Acceleration

Structural damage functions are expressed in terms of an equivalent value of PGA (rather than spectral displacement) for evaluation of buildings that are components of utility and transportation systems. Only structural damage functions are developed based on PGA, since structural damage is considered the most appropriate measure of damage for utility and transportation system facilities. Similar methods could be used to develop nonstructural damage functions based on PGA. In this case, capacity curves are not necessary to estimate building response and PGA is used directly as the PEH input to building fragility curves. This section develops equivalent-PGA fragility curves based on the structural damage functions of Table 5-12, Table 5-13, Table 5-14, and Table 5-15 and standard spectrum shape properties. Currently, the Hazus transportation and utility system facilities are not classified into the Hazus specific building types as presented in these tables. As a result, the PGA-based fragilities presented in this section are not currently used in Hazus, however, they are presented as guidance and for potential use if a user has transportation and utility system facility inventories classified into Hazus specific building types.

Median values of equivalent-PGA fragility curves are based on median values of spectral displacement of the damage state of interest and an assumed demand spectrum shape that relates spectral response to PGA. As such, median values of equivalent PGA are very sensitive to the shape assumed for the demand spectrum (i.e., PEH-input spectrum reduced for damping greater than 5% of critical as described in Section 5.6.1.1). Spectrum shape is influenced by earthquake source (i.e., WUS vs. CEUS attenuation functions), earthquake magnitude (e.g., large vs. small magnitude events), distance from source to site, site conditions (e.g., soil vs. rock), and effective damping, which varies based on building properties and earthquake duration (e.g., short, moderate, or long duration).

It is not practical to create equivalent-PGA fragility curves for all possible factors that influence demand spectrum shape. Rather, equivalent-PGA fragility curves are developed for a single set of spectrum shape factors (a reference spectrum), and a formula is provided for modifying damage state medians to approximate other spectrum shapes. The reference spectrum represents ground shaking of a large magnitude (i.e., $\mathbf{M} \cong 7.0$) western United States (WUS) earthquake for soil sites (e.g., Site Class D) at site-to-source distances of 15 km or greater. The demand spectrum based on these assumptions is scaled uniformly at each period such that the spectrum intersects the building capacity curve at the spectral displacement of the median value of the damage state of interest. The PGA of the scaled demand spectrum defines the median value of equivalent-PGA fragility. Figure 5-6 illustrates this scaling and intersection process for a typical building capacity curve and Slight, Moderate, Extensive, and Complete structural damage states.

The total variability of each equivalent-PGA structural damage state, β_{SPGA}, is modeled by the combination of following two contributors to damage variability:

- Uncertainty in the damage-state threshold of the structural system: $\beta_{M(SPGA)}$ = 0.4 for all building types and damage states)
- Variability in response due to the spatial variability of ground motion demand: $\beta_{D(V)}$ = 0.5 for long-period spectral response)

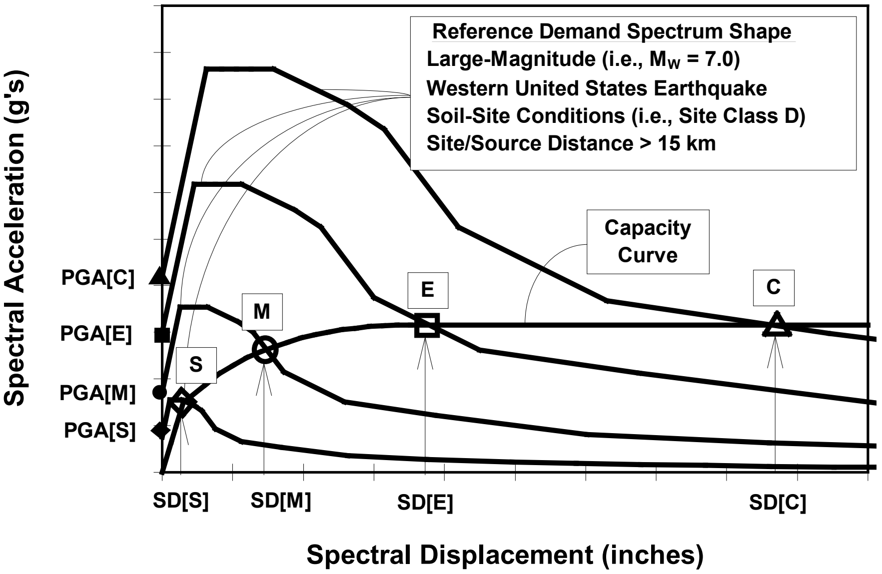


Figure 5-6 Development of Equivalent-PGA Median Damage Values

The two contributors to damage state variability are assumed to be lognormally distributed, independent random variables and the total variability is simply the SRSS combination of individual variability terms. Table 5-28, Table 5-29, Table 5-30, and Table 5-31 summarize median and lognormal standard deviation (β_{SPGA}) values for Slight, Moderate, Extensive, and Complete PGA-based structural damage states for High-Code, Moderate-Code, Low-Code, and Pre-Code buildings, respectively.

The values given in Table 5-28, Table 5-29, Table 5-30, and Table 5-31 are appropriate for use in the evaluation of scenario earthquakes whose demand spectrum shape is based on, or similar to, large magnitude, WUS ground shaking at soil sites (reference spectrum shape). For evaluation of building damage due to scenario earthquakes whose spectra are not similar to the reference spectrum shape, damage state median parameters may be adjusted to better represent equivalent-PGA structural fragility for the spectrum shape of interest. This adjustment is based on: 1) site condition (if different from Site Class D) and 2) the ratio of long-period spectral response (i.e., S_{A1}) to PGA (if different from a value of 1.5, the ratio of S_{A1} to PGA of the reference spectrum shape). Damage state variability is not adjusted, assuming that the variability associated with ground shaking (although different for different source/site conditions) when combined with the uncertainty in damage state threshold, is approximately the same for all demand spectrum shapes.

Table 4-2 provides spectral acceleration response factors for WUS rock (Site Class B) and CEUS rock (Site Class B) locations. These data are based on the default WUS and CEUS attenuation functions and describe response ratios, S_{AS}/PGA and S_{AS}/S_{A1}, as a function of distance and earthquake magnitude. Although both short-period response (S_{AS}) and long-period response (SA1) can influence building fragility, long-period response typically dominates building fragility and is the parameter used to relate spectral demand to PGA. Spectral response factors given in Table 4-2 are combined to form ratios of PGA/S_{A1} as given in Table 5-26 and Table 5-27, respectively, for different earthquake magnitudes and source/site distances.

Table 5-26 Spectrum Shape Ratio, R_{PGA}/S_{A1} - WUS Rock (Site Class B)

Closest Distance to Fault Rupture	PGA/S_{A1} Given Magnitude, M:			
	≤ 5	6	7	≥ 8
≤ 10 km	3.8	2.1	1.5	0.85
20 km	3.3	1.8	1.2	0.85
40 km	2.9	1.6	1.05	0.80
≥ 80 km	3.2	1.7	1.0	0.75

Table 5-27 Spectrum Shape Ratio, R_{PGA}/S_{A1} - CEUS Rock (Site Class B)

Hypocentral Distance	PGA/S_{A1} Given Magnitude, M:			
	≤ 5	6	7	≥ 8
≤ 10 km	7.8	3.5	2.1	1.1
20 km	8.1	3.1	2.1	1.7
40 km	6.1	2.6	1.8	1.6
≥ 80 km	4.3	1.9	1.4	1.3

Equivalent-PGA medians specified in Table 5-28, Table 5-29, Table 5-30, and Table 5-31 for the reference spectrum shape could be converted to medians representing other spectrum shapes using the ratios of Table 5-26 and Table 5-27, the soil amplification factor, FV, and Equation 5-6:

Equation 5-6

$$\overline{\mathrm{PGA}}_{ds} = \overline{\mathrm{PGA}}_{R,ds} * R_{PGA/SA1} * \left(\frac{1.5}{F_V}\right)$$

Where:

$\overline{\mathrm{PGA}}_{ds}$ is the median PGA of structural damage state, ds,

$\overline{\mathrm{PGA}}_{R,ds}$ is the median PGA of structural damage state, ds, as given in Table 5-28, Table 5-29, Table 5-30, and Table 5-31 for the reference spectrum shape

$R_{PGA/SA1}$ is the spectrum shape ratio, given in Table 5-26 and Table 5-27, and

F_V is the soil amplification factor, given in Table 4-7

In general, implementation of Equation 5-6 requires information on earthquake magnitude and source-to-site distance to estimate the spectrum shape ratio for rock sites, and 1-second period spectral acceleration at the site (to estimate the soil amplification factor). Note that for Table 5-28, Table 5-29, Table 5-30, and Table 5-31, shaded boxes indicate types that are not permitted by current seismic codes.

Table 5-28 Equivalent-PGA Structural Fragility - High-Code Seismic Design Level

Building Type	Median Equivalent-PGA (g) and Logstandard Deviation (Beta)							
	Slight		Moderate		Extensive		Complete	
	Median	Beta	Median	Beta	Median	Beta	Median	Beta
W1	0.26	0.64	0.55	0.64	1.28	0.64	2.01	0.64
W2	0.26	0.64	0.56	0.64	1.15	0.64	2.08	0.64
S1L	0.19	0.64	0.31	0.64	0.64	0.64	1.49	0.64
S1M	0.14	0.64	0.26	0.64	0.62	0.64	1.43	0.64
S1H	0.10	0.64	0.21	0.64	0.52	0.64	1.31	0.64
S2L	0.24	0.64	0.41	0.64	0.76	0.64	1.46	0.64
S2M	0.14	0.64	0.27	0.64	0.73	0.64	1.62	0.64
S2H	0.11	0.64	0.22	0.64	0.65	0.64	1.60	0.64
S3	0.15	0.64	0.26	0.64	0.54	0.64	1.00	0.64
S4L	0.24	0.64	0.39	0.64	0.71	0.64	1.33	0.64
S4M	0.16	0.64	0.28	0.64	0.73	0.64	1.56	0.64
S4H	0.13	0.64	0.25	0.64	0.69	0.64	1.63	0.64
S5L*								
S5M*								
S5H*								
C1L	0.21	0.64	0.35	0.64	0.70	0.64	1.37	0.64
C1M	0.15	0.64	0.27	0.64	0.73	0.64	1.61	0.64
C1H	0.11	0.64	0.22	0.64	0.62	0.64	1.35	0.64
C2L	0.24	0.64	0.45	0.64	0.90	0.64	1.55	0.64
C2M	0.17	0.64	0.36	0.64	0.87	0.64	1.95	0.64
C2H	0.12	0.64	0.29	0.64	0.82	0.64	1.87	0.64
C3L*								
C3M*								
C3H*								
PC1	0.20	0.64	0.35	0.64	0.72	0.64	1.25	0.64
PC2L	0.24	0.64	0.36	0.64	0.69	0.64	1.23	0.64
PC2M	0.17	0.64	0.29	0.64	0.67	0.64	1.51	0.64
PC2H	0.12	0.64	0.23	0.64	0.63	0.64	1.49	0.64
RM1L	0.30	0.64	0.46	0.64	0.93	0.64	1.57	0.64
RM1M	0.20	0.64	0.37	0.64	0.81	0.64	1.90	0.64
RM2L	0.26	0.64	0.42	0.64	0.87	0.64	1.49	0.64
RM2M	0.17	0.64	0.33	0.64	0.75	0.64	1.83	0.64
RM2H	0.12	0.64	0.24	0.64	0.67	0.64	1.78	0.64
URML*								
URMM*								
MH	0.11	0.64	0.18	0.64	0.31	0.64	0.60	0.64

**Shaded boxes and building types with an asterisk (*) indicate types that are not permitted by current seismic codes.*

Table 5-29 Equivalent-PGA Structural Fragility -Moderate-Code Seismic Design Level

Building Type	Median Equivalent-PGA (g) and Logstandard Deviation (Beta)							
	Slight		Moderate		Extensive		Complete	
	Median	Beta	Median	Beta	Median	Beta	Median	Beta
W1	0.24	0.64	0.43	0.64	0.91	0.64	1.34	0.64
W2	0.20	0.64	0.35	0.64	0.64	0.64	1.13	0.64
S1L	0.15	0.64	0.22	0.64	0.42	0.64	0.80	0.64
S1M	0.13	0.64	0.21	0.64	0.44	0.64	0.82	0.64
S1H	0.10	0.64	0.18	0.64	0.39	0.64	0.78	0.64
S2L	0.20	0.64	0.26	0.64	0.46	0.64	0.84	0.64
S2M	0.14	0.64	0.22	0.64	0.53	0.64	0.97	0.64
S2H	0.11	0.64	0.19	0.64	0.49	0.64	1.02	0.64
S3	0.13	0.64	0.19	0.64	0.33	0.64	0.60	0.64
S4L	0.19	0.64	0.26	0.64	0.41	0.64	0.78	0.64
S4M	0.14	0.64	0.22	0.64	0.51	0.64	0.92	0.64
S4H	0.12	0.64	0.21	0.64	0.51	0.64	0.97	0.64
S5L*								
S5M*								
S5H*								
C1L	0.16	0.64	0.23	0.64	0.41	0.64	0.77	0.64
C1M	0.13	0.64	0.21	0.64	0.49	0.64	0.89	0.64
C1H	0.11	0.64	0.18	0.64	0.41	0.64	0.74	0.64
C2L	0.18	0.64	0.30	0.64	0.49	0.64	0.87	0.64
C2M	0.15	0.64	0.26	0.64	0.55	0.64	1.02	0.64
C2H	0.12	0.64	0.23	0.64	0.57	0.64	1.07	0.64
C3L*								
C3M*								
C3H*								
PC1	0.18	0.64	0.24	0.64	0.44	0.64	0.71	0.64
PC2L	0.18	0.64	0.25	0.64	0.40	0.64	0.74	0.64
PC2M	0.15	0.64	0.21	0.64	0.45	0.64	0.86	0.64
PC2H	0.12	0.64	0.19	0.64	0.46	0.64	0.90	0.64
RM1L	0.22	0.64	0.30	0.64	0.50	0.64	0.85	0.64
RM1M	0.18	0.64	0.26	0.64	0.51	0.64	1.03	0.64
RM2L	0.20	0.64	0.28	0.64	0.47	0.64	0.81	0.64
RM2M	0.16	0.64	0.23	0.64	0.48	0.64	0.99	0.64
RM2H	0.12	0.64	0.20	0.64	0.48	0.64	1.01	0.64
URML*								
URMM*								
MH	0.11	0.64	0.18	0.64	0.31	0.64	0.60	0.64

**Shaded boxes and building types with an asterisk (*) indicate types that are not permitted by current seismic codes.*

Table 5-30 Equivalent-PGA Structural Fragility - Low-Code Seismic Design Level

Building Type	Median Equivalent-PGA (g) and Logstandard Deviation (Beta)							
	Slight		Moderate		Extensive		Complete	
	Median	Beta	Median	Beta	Median	Beta	Median	Beta
W1	0.20	0.64	0.34	0.64	0.61	0.64	0.95	0.64
W2	0.14	0.64	0.23	0.64	0.48	0.64	0.75	0.64
S1L	0.12	0.64	0.17	0.64	0.30	0.64	0.48	0.64
S1M	0.12	0.64	0.18	0.64	0.29	0.64	0.49	0.64
S1H	0.10	0.64	0.15	0.64	0.28	0.64	0.48	0.64
S2L	0.13	0.64	0.17	0.64	0.30	0.64	0.50	0.64
S2M	0.12	0.64	0.18	0.64	0.35	0.64	0.58	0.64
S2H	0.11	0.64	0.17	0.64	0.36	0.64	0.63	0.64
S3	0.10	0.64	0.13	0.64	0.20	0.64	0.38	0.64
S4L	0.13	0.64	0.16	0.64	0.26	0.64	0.46	0.64
S4M	0.12	0.64	0.17	0.64	0.31	0.64	0.54	0.64
S4H	0.12	0.64	0.17	0.64	0.33	0.64	0.59	0.64
S5L	0.13	0.64	0.17	0.64	0.28	0.64	0.45	0.64
S5M	0.11	0.64	0.18	0.64	0.34	0.64	0.53	0.64
S5H	0.10	0.64	0.18	0.64	0.35	0.64	0.58	0.64
C1L	0.12	0.64	0.15	0.64	0.27	0.64	0.45	0.64
C1M	0.12	0.64	0.17	0.64	0.32	0.64	0.54	0.64
C1H	0.10	0.64	0.15	0.64	0.27	0.64	0.44	0.64
C2L	0.14	0.64	0.19	0.64	0.30	0.64	0.52	0.64
C2M	0.12	0.64	0.19	0.64	0.38	0.64	0.63	0.64
C2H	0.11	0.64	0.19	0.64	0.38	0.64	0.65	0.64
C3L	0.12	0.64	0.17	0.64	0.26	0.64	0.44	0.64
C3M	0.11	0.64	0.17	0.64	0.32	0.64	0.51	0.64
C3H	0.09	0.64	0.16	0.64	0.33	0.64	0.53	0.64
PC1	0.13	0.64	0.17	0.64	0.25	0.64	0.45	0.64
PC2L	0.13	0.64	0.15	0.64	0.24	0.64	0.44	0.64
PC2M	0.11	0.64	0.16	0.64	0.31	0.64	0.52	0.64
PC2H	0.11	0.64	0.16	0.64	0.31	0.64	0.55	0.64
RM1L	0.16	0.64	0.20	0.64	0.29	0.64	0.54	0.64
RM1M	0.14	0.64	0.19	0.64	0.35	0.64	0.63	0.64
RM2L	0.14	0.64	0.18	0.64	0.28	0.64	0.51	0.64
RM2M	0.12	0.64	0.17	0.64	0.34	0.64	0.60	0.64
RM2H	0.11	0.64	0.17	0.64	0.35	0.64	0.62	0.64
URML	0.14	0.64	0.20	0.64	0.32	0.64	0.46	0.64
URMM	0.10	0.64	0.16	0.64	0.27	0.64	0.46	0.64
MH	0.11	0.64	0.18	0.64	0.31	0.64	0.60	0.64

Table 5-31 Equivalent-PGA Structural Fragility - Pre-Code Seismic Design Level

Building Type	Median Equivalent-PGA (g) and Logstandard Deviation (Beta)							
	Slight		Moderate		Extensive		Complete	
	Median	Beta	Median	Beta	Median	Beta	Median	Beta
W1	0.18	0.64	0.29	0.64	0.51	0.64	0.77	0.64
W2	0.12	0.64	0.19	0.64	0.37	0.64	0.60	0.64
S1L	0.09	0.64	0.13	0.64	0.22	0.64	0.38	0.64
S1M	0.09	0.64	0.14	0.64	0.23	0.64	0.39	0.64
S1H	0.08	0.64	0.12	0.64	0.22	0.64	0.38	0.64
S2L	0.11	0.64	0.14	0.64	0.23	0.64	0.39	0.64
S2M	0.10	0.64	0.14	0.64	0.28	0.64	0.47	0.64
S2H	0.09	0.64	0.13	0.64	0.29	0.64	0.50	0.64
S3	0.08	0.64	0.10	0.64	0.16	0.64	0.30	0.64
S4L	0.10	0.64	0.13	0.64	0.20	0.64	0.36	0.64
S4M	0.09	0.64	0.13	0.64	0.25	0.64	0.43	0.64
S4H	0.09	0.64	0.14	0.64	0.27	0.64	0.47	0.64
S5L	0.11	0.64	0.14	0.64	0.22	0.64	0.37	0.64
S5M	0.09	0.64	0.14	0.64	0.28	0.64	0.43	0.64
S5H	0.08	0.64	0.14	0.64	0.29	0.64	0.46	0.64
C1L	0.10	0.64	0.12	0.64	0.21	0.64	0.36	0.64
C1M	0.09	0.64	0.13	0.64	0.26	0.64	0.43	0.64
C1H	0.08	0.64	0.12	0.64	0.21	0.64	0.35	0.64
C2L	0.11	0.64	0.15	0.64	0.24	0.64	0.42	0.64
C2M	0.10	0.64	0.15	0.64	0.30	0.64	0.50	0.64
C2H	0.09	0.64	0.15	0.64	0.31	0.64	0.52	0.64
C3L	0.10	0.64	0.14	0.64	0.21	0.64	0.35	0.64
C3M	0.09	0.64	0.14	0.64	0.25	0.64	0.41	0.64
C3H	0.08	0.64	0.13	0.64	0.27	0.64	0.43	0.64
PC1	0.11	0.64	0.14	0.64	0.21	0.64	0.35	0.64
PC2L	0.10	0.64	0.13	0.64	0.19	0.64	0.35	0.64
PC2M	0.09	0.64	0.13	0.64	0.24	0.64	0.42	0.64
PC2H	0.09	0.64	0.13	0.64	0.25	0.64	0.43	0.64
RM1L	0.13	0.64	0.16	0.64	0.24	0.64	0.43	0.64
RM1M	0.11	0.64	0.15	0.64	0.28	0.64	0.50	0.64
RM2L	0.12	0.64	0.15	0.64	0.22	0.64	0.41	0.64
RM2M	0.10	0.64	0.14	0.64	0.26	0.64	0.47	0.64
RM2H	0.09	0.64	0.13	0.64	0.27	0.64	0.50	0.64
URML	0.13	0.64	0.17	0.64	0.26	0.64	0.37	0.64
URMM	0.09	0.64	0.13	0.64	0.21	0.64	0.38	0.64
MH	0.08	0.64	0.11	0.64	0.18	0.64	0.34	0.64

5.5 Building Damage Due to Ground Failure

Building damage is characterized by four damage states (i.e., Slight, Moderate, Extensive, and Complete). These four states are simplified for ground failure to include only one combined Extensive/Complete damage state. In essence, buildings are assumed to be either undamaged or severely damaged due to ground failure. In fact, Slight or Moderate damage can occur due to ground failure, but the likelihood of this damage is considered to be small (relative to ground shaking damage) and tacitly included in predictions of Slight or Moderate damage due to ground shaking.

Given the earthquake demand in terms of permanent ground deformation (PGD), the probability of being in the Extensive/Complete damage state is estimated using fragility curves of a form similar to those used to estimate shaking damage. Separate fragility curves distinguish between ground failure due to lateral spreading and ground failure due to ground settlement, and between shallow and deep foundations. By default, Hazus assumes all buildings are on shallow foundations.

5.5.1 Fragility Curves – Peak Ground Displacement

There is no available relationship between the likelihood of Extensive/Complete damage to buildings and PGD. Engineering judgment has been used to develop a set of assumptions which define building fragility. These assumptions are shown in Table 5-32 for buildings with shallow foundations (e.g., spread footings).

Table 5-32 Building Damage Relationship to PGD – Shallow Foundations

$P[E \text{ or } C \mid PGD]$	Settlement PGD (inches)	Lateral Spread PGD (inches)
0.1	2	12
0.5 (median)	10	60

The above assumptions are based on the expectation that about 10 (i.e., 8 Extensive damage, 2 Complete damage) out of 100 buildings on spread footings would be severely damaged for 2 inches of settlement PGD or 12 inches of lateral spread PGD, and that about 50 (i.e., 40 Extensive damage, 10 Complete damage) out of 100 buildings on spread footings would be severely damaged for 10 inches of settlement PGD or 60 inches of lateral spread PGD. Lateral spread is judged to require significantly more PGD to effect severe damage than ground settlement. Many buildings in lateral spread areas are expected to move with the spread, but not to be severely damaged until the spread becomes quite significant.

Median PGD values given in Table 5-32 are used with a lognormal standard deviation value of β_{PGD}= 1.2 to estimate P[E or C|PGD] for buildings on shallow foundations. The value of β_{PGD}= 1.2 is based on the factor of 5 between the PGD values at the 10 and 50 percentile levels.

No attempt is made to distinguish damage based on building type, since model building descriptions do not include foundation type. Foundation type is critical to PGD performance and buildings on deep foundations (e.g., piles) perform much better than buildings on spread footings, if the ground settles. When the building is known to be supported by a deep foundation, the probability of Extensive or Complete damage is reduced by a factor of 10 from that predicted for settlement-induced damage of the same building on a shallow foundation. Deep foundations will improve building performance by only a limited amount if the ground spreads laterally. When the building is known to be supported by a deep foundation, the probability of Extensive or Complete damage is reduced by a factor of 2 from that predicted for spread-induced damage of the same building on a shallow foundation.

5.6 Evaluation of Building Damage

During an earthquake, a building may be damaged either by ground shaking, ground failure, or both. Buildings are evaluated separately for the two modes of failure; the resulting damage-state probabilities are combined for evaluation of loss.

5.6.1 Damage Due to Ground Shaking

This section describes the process of developing damage state probabilities based on structural and nonstructural fragility curves, model building capacity curves, and a demand spectrum. Building response (e.g., peak displacement) is determined by the intersection of the demand spectrum and the building capacity curve. The demand spectrum is based on the PEH input spectrum reduced for effective damping (when effective damping exceeds the 5% damping level of the PEH input spectrum).

5.6.1.1 Demand Spectrum Reduction for Effective Damping

The elastic response spectra provided as a PEH input apply only to buildings that remain elastic during the entire ground shaking time history and have elastic damping values equal to 5% of critical. This is generally not true on both accounts. Therefore, two modifications are made to elastic response spectra: (a) demand spectra are modified for buildings with elastic damping not equal to 5%, and (b) demand spectra are modified for the hysteretic energy dissipated by buildings “pushed” beyond their elastic limits. Modifications are represented by reduction factors by which the spectral ordinates are divided to obtain the damped demand spectra.

Extensive work has been published on the effect of damping and/or energy dissipation on spectral demand. The Hazus Methodology reduces demand spectra for effective damping greater than 5% based on statistically-based formulas of Newmark and Hall (1982). Other methods are available for estimating spectral reduction factors based on statistics relating reduction to ductility demand. It is believed that both methods yield the same results for most practical purposes (FEMA 273, 1996a). Newmark and Hall provide formulas for construction of elastic response spectra at different damping ratios, B (expressed as a percentage). These formulas represent all site classes (soil types) distinguishing between domains of constant acceleration and constant velocity. Ratios of these formulas are used to develop an acceleration-domain (short-period) reduction factor, RA, and a velocity-domain (1-second spectral acceleration) reduction factor, RV, for modification of 5%-damped, elastic response spectra (PEH input). These reduction factors are based on effective damping, Beff, as given in Equation 5-7 and Equation 5-8 below:

Equation 5-7

$$\mathrm{R_A} = \frac{2.12}{3.21 - 0.68 * \ln \mathrm{B_{eff}}}$$

Equation 5-8

$$\mathrm{R_V} = \frac{1.65}{2.31 - 0.41 * \ln \mathrm{B_{eff}}}$$

for which effective damping is defined as the sum of elastic damping, B_E, and hysteretic damping, B_H:

Equation 5-9

$$B_{eff} = B_E + B_H$$

Elastic damping, B_E, is dependent on structure type and is based on the recommendations of Newmark and Hall for materials at or just below their yield point. Hysteretic damping, B_H, is dependent on the amplitude of response and is based on the area enclosed by the hysteresis loop, considering potential degradation of energy-absorption capacity of the structure during cyclic earthquake load (for more detailed information, refer to a traditional engineering reference on structural dynamics, such as “Dynamics of Structures”, Chopra, 1995). Effective damping, Beff, is also a function of the amplitude of response (e.g., peak displacement), as expressed in Equation 5-10 below.

Equation 5-10

$$B_{eff} = B_E + \kappa * \left(\frac{\text{Area}}{2\pi * D * A}\right)$$

Where:

Beff	is the effective damping
B_E	is the elastic (pre-yield) damping of the specific building type
Area	is the area enclosed by the hysteresis loop, as defined by a symmetrical push-pull of the building capacity curve up to peak positive and negative displacements, ± D
D	is the peak displacement response of the push-over curve,
A	is the peak acceleration response at peak displacement, D
K	is a degradation factor that defines the effective amount of hysteretic damping as a function of earthquake duration, as specified in Table 5-33.

Table 5-33 Degradation Factor (k) as a Function of Short, Moderate and Long Earthquake Duration

Building Type		High-Code Design			Moderate-Code Design			Low-Code Design			Pre-Code Design		
No	**Label**	**Short**	**Moderate**	**Long**	**Short**	**Moderate**	**Long**	**Short**	**Moderate**	**Long**	**Short**	**Moderate**	**Long**
1	W1	1.00	0.80	0.50	0.90	0.60	0.30	0.70	0.40	0.20	0.50	0.30	0.10
2	W2	0.90	0.60	0.40	0.80	0.40	0.20	0.60	0.30	0.10	0.40	0.20	0.00
3	S1L	0.90	0.60	0.40	0.80	0.40	0.20	0.60	0.30	0.10	0.40	0.20	0.00
4	S1M	0.90	0.60	0.40	0.80	0.40	0.20	0.60	0.30	0.10	0.40	0.20	0.20
5	S1H	0.90	0.60	0.40	0.80	0.40	0.20	0.60	0.30	0.10	0.40	0.20	0.20
6	S2L	0.70	0.50	0.30	0.60	0.40	0.20	0.50	0.30	0.10	0.40	0.20	0.00
7	S2M	0.70	0.50	0.30	0.60	0.40	0.20	0.50	0.30	0.10	0.40	0.20	0.00
8	S2H	0.70	0.50	0.30	0.60	0.40	0.20	0.50	0.30	0.10	0.40	0.20	0.00
9	S3	0.70	0.50	0.30	0.60	0.40	0.20	0.50	0.30	0.10	0.40	0.20	0.00
10	S4L	0.70	0.50	0.30	0.60	0.40	0.20	0.50	0.30	0.10	0.40	0.20	0.00
11	S4M	0.70	0.50	0.30	0.60	0.40	0.20	0.50	0.30	0.10	0.40	0.20	0.00
12	S4H	0.70	0.50	0.30	0.60	0.40	0.20	0.50	0.30	0.10	0.40	0.20	0.00
13	S5L	0.50	0.30	0.10	0.50	0.30	0.10	0.50	0.30	0.10	0.40	0.20	0.00
14	S5M	0.50	0.30	0.10	0.50	0.30	0.10	0.50	0.30	0.10	0.40	0.20	0.00
15	S5H	0.50	0.30	0.10	0.50	0.30	0.10	0.50	0.30	0.10	0.40	0.20	0.00
16	C1L	0.90	0.60	0.40	0.80	0.40	0.20	0.60	0.30	0.10	0.40	0.20	0.00
17	C1M	0.90	0.60	0.40	0.80	0.40	0.20	0.60	0.30	0.10	0.40	0.20	0.00
18	C1H	0.90	0.60	0.40	0.80	0.40	0.20	0.60	0.30	0.10	0.40	0.20	0.00
19	C2L	0.90	0.60	0.40	0.80	0.40	0.20	0.60	0.30	0.10	0.40	0.20	0.00
20	C2M	0.90	0.60	0.40	0.80	0.40	0.20	0.60	0.30	0.10	0.40	0.20	0.00
21	C2H	0.90	0.60	0.40	0.80	0.40	0.20	0.60	0.30	0.10	0.40	0.20	0.00
22	C3L	0.50	0.30	0.10	0.50	0.30	0.10	0.50	0.30	0.10	0.40	0.20	0.00
23	C3M	0.50	0.30	0.10	0.50	0.30	0.10	0.50	0.30	0.10	0.40	0.20	0.00
24	C3H	0.50	0.30	0.10	0.50	0.30	0.10	0.50	0.30	0.10	0.40	0.20	0.00
25	PC1	0.70	0.50	0.30	0.60	0.40	0.20	0.50	0.30	0.10	0.40	0.20	0.00
26	PC2L	0.70	0.50	0.30	0.60	0.40	0.20	0.50	0.30	0.10	0.40	0.20	0.00
27	PC2M	0.70	0.50	0.30	0.60	0.40	0.20	0.50	0.30	0.10	0.40	0.20	0.00
28	PC2H	0.70	0.50	0.30	0.60	0.40	0.20	0.50	0.30	0.10	0.40	0.20	0.00
29	RM1L	0.90	0.60	0.40	0.80	0.40	0.20	0.60	0.30	0.10	0.40	0.20	0.00
30	RM1M	0.90	0.60	0.40	0.80	0.40	0.20	0.60	0.30	0.10	0.40	0.20	0.00
31	RM2L	0.90	0.60	0.40	0.80	0.40	0.20	0.60	0.30	0.10	0.40	0.20	0.00
32	RM2M	0.90	0.60	0.40	0.80	0.40	0.20	0.60	0.30	0.10	0.40	0.20	0.00
33	RM2H	0.90	0.60	0.40	0.80	0.40	0.20	0.60	0.30	0.10	0.40	0.20	0.00
34	URML	0.50	0.30	0.10	0.50	0.30	0.10	0.50	0.30	0.10	0.40	0.20	0.00
35	URMM	0.50	0.30	0.10	0.50	0.30	0.10	0.50	0.30	0.10	0.40	0.20	0.00
36	MH	0.80	0.40	0.20	0.80	0.40	0.20	0.80	0.40	0.20	0.60	0.30	0.10

The methodology recognizes the importance of the duration of ground shaking on building response by reducing effective damping (i.e., k factors) as a function of shaking duration. Shaking duration is described qualitatively as either Short, Moderate, or Long, and is assumed to be a function of earthquake magnitude (although proximity to fault rupture also influences the duration of ground shaking). For scenario earthquakes of magnitude **M** ≤ 5.5, effective damping is based on the assumption of ground shaking of Short duration. For scenario earthquakes of magnitude **M** ≥ 7.5, effective damping is based on the assumption of ground shaking of Long duration. Effective damping is based on the assumption of Moderate duration for all other earthquake magnitudes. All scenario types require that the user provide the magnitude for the purpose of classifying duration, including probabilistic analyses. However, for average annualized loss (AAL) analysis the assumption is that the 100 and 200 year ground motions are Short duration, 500, 750 and 1,000 year are Moderate duration, and 1,500, 2,000 and 2,500 year are driven by Long duration magnitudes.

5.6.1.2 Construction of Demand Spectra

Demand spectral acceleration, $S_A[T]$, in units of acceleration (g) is defined by Equation 5 11 at short periods (acceleration domain), Equation 5-12 at long periods (velocity domain), and Equation 5-13 at very long periods (displacement domain).

At short $0 < T \leq T_{AV\beta}$ periods,

Equation 5-11

$$S_A[T] = \frac{S_{ASi}}{R_A[B_{eff}]} = \frac{S_{ASi}}{\frac{2.12}{3.21 - 0.68 \ln (B_{eff})}}$$

At long $T_{AV\beta} < T \leq T_{VD}$periods,

Equation 5-12

$$S_A[T] = \frac{\frac{S_{A1i}}{T}}{R_v(B_{eff})} = \frac{\frac{S_{A1i}}{T}}{\frac{1.65}{2.31 - 0.41(\ln B_{eff})}}$$

At very long $T > T_{VD}$ periods,

Equation 5-13

$$S_A[T] = \frac{\frac{S_{A1i} * T_{VD}}{T^2}}{R_v[B_{TVD}]} = \frac{\frac{S_{A1i} * T_{VD}}{T^2}}{\frac{1.65}{2.31 - 0.41(\ln B_{TVD})}}$$

Where:

S_{ASi}	is the 5%-damped, short-period spectral acceleration for Site Class i (in units of g), as defined in Equation 4-6.
S_{A1i}	is the 5%-damped, 1-second-period spectral acceleration for Site Class i (units of g), as defined in Equation 4-7 times 1 second
T_{AVi}	is the transition period between 5%-damped constant spectral acceleration and 5%-damped constant spectral velocity for Site Class i (sec.), as defined in Equation 4-8

B_{TVD} is the value of effective damping at the transition period, T_{VD}

B_{TAVB} is the value of effective damping at the transition period, $T_{AV\beta}$

The transition period, T_{AVB}, between acceleration and velocity domains is a function of the effective damping at this period, as defined by Equation 5-14. The transition period, T_{VD}, between velocity and displacement domains is independent of effective damping.

Equation 5-14

$$T_{AVB} = T_{AVi}\left(\frac{R_A[B_{TAVB}]}{R_V[B_{TAVB}]}\right) = T_{AVi}\left(\frac{2.12/(3.21 - 0.68\ln(B_{TAVB}))}{1.65/(2.31 - 0.41\ln(B_{TAVB}))}\right)$$

Demand spectral displacement, $S_D[T]$, in inches, is based on $S_A[T]$, in units of g, as given in Equation 5-15.

Equation 5-15

$$S_D[T] = 9.8 * S_A[T] * T^2$$

Figure 5-7 shows typical demand spectra (spectral acceleration plotted as a function of spectral displacement) for three demand levels, estimated for M=7.0 at 20 km, for the WUS, on Site Class E. These three demand levels represent Short (k = 0.80), Moderate (k = 0.40) and Long (k = 0.20) duration ground shaking, respectively. Also shown in the figure is the building capacity curve of a low-rise building of Moderate-Code seismic design that was used to estimate effective damping. The intersection of the capacity curve with each of the three demand spectra illustrates the significance of duration (damping) on building response.

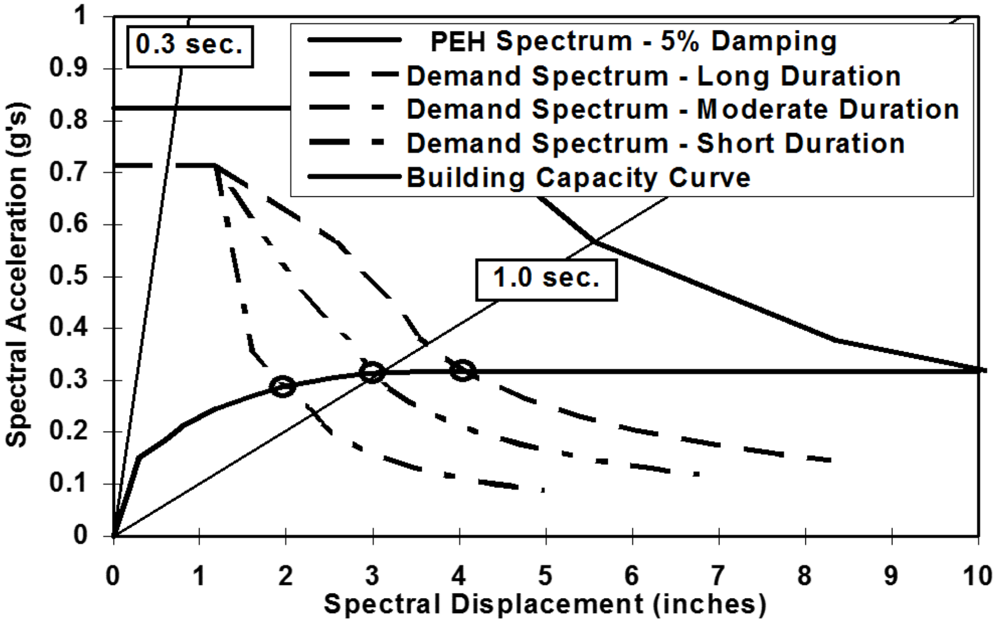


Figure 5-7 Example Demand Spectra - Moderate-Code Building

5.6.1.3 Damage State Probability

Structural and nonstructural fragility curves are evaluated for spectral displacement and spectral acceleration defined by the intersection of the capacity and demand curves. Each of these curves describes the cumulative probability of being in, or exceeding, a particular damage state.

Nonstructural components (both drift- and acceleration-sensitive components) may, in some cases, be dependent on the structural damage state (e.g., Complete structural damage may cause complete nonstructural damage). The methodology assumes nonstructural damage states to be independent of structural damage states. Cumulative probabilities are differenced to obtain discrete probabilities of being in each of the five damage states.

It is also meaningful to interpret damage probabilities as the fraction of all buildings (of the same type) that would be in the particular damage state of interest. For example, a 30% probability of Moderate damage may also be thought of as 30 out of 100 buildings (of the same type) being in the Moderate damage state.

5.6.2 Combined Damage Due to Ground Failure and Ground Shaking

This section describes the combination of damage state probabilities due to ground failure and ground shaking. It is assumed that damage due to ground shaking (GS) is independent of damage due to ground failure (GF). Ground failure tends to cause severe damage to buildings and is assumed to contribute only to Extensive and Complete damage states (refer to Section 5.5.1). Equation 5-16 and Equation 5-17 demonstrate that for ground failure, the damage state exceedance probability (probability of being in or exceeding a given damage state) for Slight and Moderate damage are equal to the damage state exceedance probability for the Extensive damage state, while Equation 5-18 shows that the Complete damage state exceedance probability is equal to 20% of the Extensive damage state exceedance probability. In the following equations, DS is damage state, and the symbols S, M, E, and C represent Slight, Moderate, Extensive, and Complete damage, respectively.

Equation 5-16

$$\mathrm{P_{GF}}\,[\mathrm{DS} \geq \mathrm{S}] = \mathrm{P_{GF}}\,[\mathrm{DS} \geq \mathrm{E}]$$

Equation 5-17

$$\mathrm{P_{GF}}\,[\mathrm{DS} \geq \mathrm{M}] = \mathrm{P_{GF}}\,[\mathrm{DS} \geq \mathrm{E}]$$

Equation 5-18

$$\mathrm{P_{GF}}\,[\mathrm{DS} \geq \mathrm{C}] = 0.2 * \mathrm{P_{GF}}\,[\mathrm{DS} \geq \mathrm{E}]$$

The damage state exceedance probability for ground failure (GF) is assumed to be the maximum of the three types of ground failure (liquefaction-induced settlement, liquefaction-induced lateral spread, and landsliding). The combined probability (due to occurrence of GF or ground shaking, GS) of being in or exceeding the Slight, Moderate, Extensive, and Complete damage states are given in Equation 5-19 through Equation 5-22, respectively. In these equations, COMB indicates the combined probability for the damage state due to the occurrence of ground failure or ground shaking.

Equation 5-19

$$P_{COMB}\,[DS \geq S] = P_{GF}\,[DS \geq S] + P_{GS}\,[DS \geq S] - P_{GF}\,[DS \geq S] * P_{GS}\,[DS \geq S]$$

Equation 5-20

$$P_{COMB}\,[DS \geq M] = P_{GF}\,[DS \geq M] + P_{GS}\,[DS \geq M] - P_{GF}\,[DS \geq M] * P_{GS}\,[DS \geq M]$$

Equation 5-21

$$P_{COMB}\,[DS \geq E] = P_{GF}\,[DS \geq E] + P_{GS}\,[DS \geq E] - P_{GF}\,[DS \geq E] * P_{GS}\,[DS \geq E]$$

Equation 5-22

$$P_{COMB}\,[DS \geq C] = P_{GF}\,[DS \geq C] + P_{GS}\,[DS \geq C] - P_{GF}\,[DS \geq C] * P_{GS}\,[DS \geq C]$$

Note that the condition laid out in Equation 5-23 must always be true:

Equation 5-23

$$1 \geq P_{COMB}\,[DS \geq S] \geq P_{COMB}\,[DS \geq M] \geq P_{COMB}\,[DS \geq E] \geq P_{COMB}\,[DS \geq C]$$

From the damage state exceedance probabilities (probability of being in or exceeding a given damage state), discrete damage state occurrence probabilities (probabilities of being in a given damage state) may be derived, as shown in Equation 5-24 through Equation 5-28 for the Complete, Extensive, Moderate, Slight, and None damage states, respectively.

Equation 5-24

$$P_{COMB}\,[DS = C] = P_{COMB}\,[DS \geq C]$$

Equation 5-25

$$P_{COMB}\,[DS = E] = P_{COMB}\,[DS \geq E] - P_{COMB}\,[DS \geq C]$$

Equation 5-26

$$P_{COMB}\,[DS = M] = P_{COMB}\,[DS \geq M] - P_{COMB}\,[DS \geq E]$$

Equation 5-27

$$P_{COMB}\,[DS = S] = P_{COMB}\,[DS \geq S] - P_{COMB}\,[DS \geq M]$$

Equation 5-28

$$P_{COMB}\,[DS = \mathrm{None}] = 1 - P_{COMB}\,[DS \geq S]$$

5.6.3 Combined Damage to Occupancy Classes

The damage state probabilities for specific building types are combined to yield the damage state probabilities of the occupancy classes to which they belong. For each damage state, the probability of damage to each specific building type is weighted according to the fraction of the total floor area of that specific building type and summed over all building types. This is expressed in equation form:

Equation 5-29

$$\mathrm{POSTR}_{\mathrm{ds},\mathrm{i}} = \sum_{\mathrm{j}=1}^{36}\left[\mathrm{PMBTSTR}_{\mathrm{ds},\mathrm{j}} * \frac{\mathrm{FA}_{\mathrm{i},\mathrm{j}}}{\mathrm{FA}_{\mathrm{i}}}\right]$$

Where:

$\mathrm{PMBTSTR}_{ds,j}$	is the probability of the specific building type, j, being in damage state, ds
$\mathrm{POSTR}_{ds,i}$	is the probability of occupancy class, i, being in damage state, ds
$\mathrm{FA}_{i,j}$	is the floor area of specific building type, j, in occupancy class, i
FA_{i}	is the total floor area of the occupancy class, i

Similarly, the damage state probabilities for nonstructural components can be estimated.

Equation 5-30

$$\mathrm{PONSD}_{\mathrm{ds},\mathrm{i}} = \sum_{\mathrm{j}=1}^{36}\left[\mathrm{PMBTNSD}_{\mathrm{ds},\mathrm{j}} * \frac{\mathrm{FA}_{\mathrm{i},\mathrm{j}}}{\mathrm{FA}_{\mathrm{i}}}\right]$$

Equation 5-31

$$\mathrm{PONSA}_{\mathrm{ds},\mathrm{i}} = \sum_{\mathrm{j}=1}^{36}\left[\mathrm{PMBTNSA}_{\mathrm{ds},\mathrm{j}} * \frac{\mathrm{FA}_{\mathrm{i},\mathrm{j}}}{\mathrm{FA}_{\mathrm{i}}}\right]$$

Where:

$\mathrm{PMBTNSD}_{ds,j}$	is the probability of specific building type, j, being in nonstructural drift-sensitive damage state, ds
$\mathrm{PMBTNSA}_{ds,j}$	is the probability of specific building type, j, being in nonstructural acceleration-sensitive damage state, ds
$\mathrm{PONSD}_{ds,i}$	is the probability of the occupancy class, i, being the nonstructural drift-sensitive damage state, ds,
$\mathrm{PONSA}_{ds,i}$	is the probability of the occupancy class, i, being the nonstructural acceleration-sensitive damage state, ds

These occupancy class probabilities are used in Section 11 to estimate direct economic loss.

5.7 Guidance for Expert Users

This section provides guidance for users who are seismic/structural experts interested in modifying the building damage functions supplied with the methodology. This section also provides the expert user with guidance regarding the selection of the appropriate mix of design levels for the region of interest.

5.7.1 Selection of Representative Seismic Design Level

The methodology permits the advanced user to select the seismic design level considered appropriate for the Study Region and to define a mix of seismic design levels for each specific building type. The building damage functions provided are based on modern code provisions (e.g., 1994 *Uniform Building Code*, 1994 *NEHRP Provisions*, or later editions of these model codes) and represent buildings of modern design and construction. The design criteria for various seismic design zones are introduced in Table 5-3. Most buildings in a Study Region will likely not be of modern design and construction (i.e., do not conform to 1994 *UBC*, 1994 *NEHRP Provisions*, or later editions of these model Codes). For many Study Regions, particularly those in the Central and Eastern United States, seismic provisions may not be enforced (or only adopted very recently). Building damage functions for new buildings designed and constructed to meet modern code provisions should not be used for older, non-complying buildings.

The building damage functions represent specific cells of a three by three matrix that defines three seismic design levels (High, Moderate, and Low) and, for each of these design levels, three seismic performance levels (Inferior, Ordinary, and Superior), as shown in Table 5-34. For completeness, cells representing Special buildings of Section 6 are also included in the matrix.

Table 5-34 Seismic Design and Performance Levels of Default Building Damage Functions (and Approximate Structural Strength and Ductility)

Seismic Design Level	Seismic Performance Level		
	Superior*	Ordinary	Inferior
High (*UBC* Zone 4)	Special High-Code *Maximum Strength* *Maximum Ductility*	High-Code *High Strength* *High Ductility*	*Moderate Strength* *Mod/Low Ductility*
Moderate (*UBC* Zone 2B)	Special Moderate-Code *High/Mod. Strength* *High Ductility*	Moderate-Code *Moderate Strength* *Moderate Ductility*	*Low Strength* *Low Ductility*
Low (*UBC* Zone 1)	Special Low-Code *Mod./Low Strength* *Moderate Ductility*	Low-Code *Low Strength* *Low Ductility*	Pre-Code *Minimal Strength* *Minimal Ductility*

** See Section 6 for Special High-Code, Moderate-Code, and Low-Code building damage functions.*

Table 5-34 also defines the approximate structural strength and ductility attributes of buildings occupying each of the nine cells.

Table 5-35 relates UBC seismic zones to seismic design regions of the NEHRP Provisions.

Expert users may tailor the damage functions to their study area of interest by determining the appropriate fraction of each building type that conforms essentially to modern code provisions (based on age of construction) and adjusting the General Building Stock's mapping schemes accordingly. Buildings deemed not to conform to modern code provisions should be assigned a lower seismic design level or defined as Pre-Code buildings if not seismically designed. For instance, older buildings located in High-Code seismic design areas should be evaluated using damage functions for either Moderate-Code buildings or Pre-Code buildings, for buildings that pre-date seismic codes.

Table 5-35 provides guidance for selecting appropriate building damage functions based on building location (i.e., seismic region) and building age. The years shown as break points are representative of major code benchmark years in California and should be considered very approximate and may not be appropriate for many seismic regions, particularly regions of low and moderate seismicity where seismic codes have not been rapidly adopted or routinely enforced. Users should develop benchmark years appropriate for their jurisdiction based on advice from building officials and engineers familiar with the code adoption and enforcement history.

Table 5-35 Guidelines for Selection of Damage Functions for Typical Buildings Based on UBC Seismic Zone and Building Age for California

UBC Seismic Zone (NEHRP Map Area)	Post-1975	1941 - 1975	Pre-1941
Zone 4 (Map Area 7)	High-Code	Moderate-Code	Pre-Code (W1 = Moderate-Code)
Zone 3 (Map Area 6)	Moderate-Code	Moderate-Code	Pre-Code (W1 = Moderate-Code)
Zone 2B (Map Area 5)	Moderate-Code	Low-Code	Pre-Code (W1 = Low-Code)
Zone 2A (Map Area 4)	Low-Code	Low-Code	Pre-Code (W1 = Low-Code)
Zone 1 (Map Area 2/3)	Low-Code	Pre-Code (W1 = Low-Code)	Pre-Code (W1 = Low-Code)
Zone 0 (Map Area 1)	Pre-Code (W1 = Low-Code)	Pre-Code (W1 = Low-Code)	Pre-Code (W1 = Low-Code)

The guidelines given in Table 5-35 assume that buildings in the Study Region are not designed for wind. The user should consider the possibility that mid-rise and high-rise buildings could be designed for wind and may have considerable lateral strength (though not ductility), even if not designed for earthquake. Users must be knowledgeable about the type and history of construction in the Study Region of interest and apply engineering judgment in assigning the fraction of each building type to a seismic design group.

5.7.2 Development of Damage Functions for Other Buildings

For a building type other than one of those discussed, expert users should select a set of building damage functions that best represents the type of construction, strength, and ductility of the building type of interest. Such buildings include rehabilitated structures that have improved seismic capacity. For example, URM (Pre-Code) buildings retrofitted in accordance with Division 88, the Los Angeles City Ordinance to “reduce the risk of life loss,” demonstrated significantly improved seismic performance during the 1994 Northridge earthquake (SSC, 1995). Structural damage to these buildings would be better estimated using either essential facility damage functions of either Special Low-Code or Special Moderate-Code RM1 buildings.

Several multi-disciplinary projects have produced Hazus-compatible damage functions, including functions for steel moment frame buildings with typical “Pre-Northridge connections” and new or retrofitted “Post-Northridge connections” developed for FEMA by the Sac Steel Project (FEMA, 2000), functions for nineteen wood frame building variants developed by the CUREE/Caltech Woodframe Project (Porter et al., 2002), and functions for retrofitted URM and eight residential wood frame building types, including soft-story conditions, developed for the City of San Francisco’s Community Action Plan for Seismic Safety (CAPSS) Project (ATC, 2010).

Section 6. Essential and High Potential Loss Facilities

This section describes methods for determining the probability of Slight, Moderate, Extensive, and Complete damage to essential facilities. These methods are identical to those of Section 5 that describe damage to Code buildings, except that certain essential facilities are represented by Special building damage functions. Special building damage functions are appropriate for evaluation of essential facilities when the user anticipates above-Code seismic performance for these facilities.

The scope of this section includes: 1) classification of essential facilities, 2) building damage functions for Special buildings, 3) methods for estimation of earthquake damage to essential facilities, given knowledge of the specific building type and seismic design level, and an estimate of earthquake demand, and 4) guidance for expert users, including estimation of damage to High Potential Loss (HPL) facilities.

6.1 Essential Facility Classification

Facilities that provide services to the community and those that should be functional following an earthquake are considered essential facilities. Examples of essential facilities include hospitals, police stations, fire stations, emergency operations centers (EOCs), and schools. The methodology adopted for damage assessment of such facilities is explained in this section.

Essential facilities are classified based on facility function and, in the case of hospitals, size. Table 6-1 lists the classes of essential facilities used in the Hazus Methodology. Hospitals are classified according to number of beds, since the structural and nonstructural systems of a hospital are related to the size of the hospital (i.e., to the number of beds it contains).

Table 6-1 Classification of Essential Facilities

No.	Label	Occupancy Class	Description
Medical Care Facilities			
1	EFHS	Small Hospitals	Hospitals with fewer than 50 Beds
2	EFHM	Medium Hospitals	Hospitals with beds between 50 & 150
3	EFHL	Large Hospitals	Hospitals with more than 150 Beds
4	EFMC	Medical Clinics	Clinics, Labs, Blood Banks
Emergency Response			
5	EFFS	Fire Stations	
6	EFPS	Police Stations	
7	EFEO	Emergency Operations Centers	
Schools			
8	EFS1	Schools	Primary/ Secondary Schools (K-12)
9	EFS2	Colleges/Universities	Community and State Colleges, State and Private Universities

Beginning with Hazus 4.2.3 released in May 2019, baseline essential facility data are directly updated from the Homeland Infrastructure Foundation-Level Data (HIFLD) Open datasets. Details on how the baseline specific building types and seismic design levels are assigned to essential facilities are provided in the *Hazus Inventory Technical Manual*. This section provides building damage functions for Special buildings that have significantly better than average seismic capacity. Section 5 provides building damage functions for Code buildings. These Special building seismic design levels should be used where appropriate, however, if unable to determine that the essential facility is significantly better than average, then the facility should be modeled using Code building damage functions (i.e., the same building damage functions as those developed in Section 5 for general building stock).

6.2 Input Requirements and Output Information

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

- Specific building type (including height) and seismic design level that represents the essential facility (or type of essential facilities) of interest.
- Response spectrum (or PGA, for transportation and utility system buildings) and PGD for ground failure evaluation at the essential facility's site.

The response spectrum, PGA, and PGD at the essential facility site are PEH outputs, described in Section 4.

The output of fragility curves is an estimate of the cumulative probability of being in or exceeding each damage state for the given level of ground shaking (or ground failure). Cumulative damage probabilities are differenced to create discrete damage state probabilities, as described in Section 5.6. Discrete probabilities of damage are used directly as inputs to induced physical damage and direct economic and social loss modules.

Typically, the specific building type (including height) is not known for each essential facility and must be inferred from the inventory of essential facilities using the occupancy/building type relationships described in the *Hazus Inventory Technical Manual*. In general, the performance of essential facilities is not expected to be better than the typical building of the representative specific building type. Exceptions to this generalization include California hospitals of recent (post-1973) construction.

6.3 Form of Damage Functions

Building damage functions for essential facilities are of the same form as those described in Section 5 for the general building stock. For each damage state, a lognormal fragility curve relates the probability of damage to PGA, PGD, or spectral demand determined by the intersection of the specific building type's capacity curve and the demand spectrum. Figure 6-1 provides an example of fragility curves for four damage states: Slight, Moderate, Extensive, and Complete.

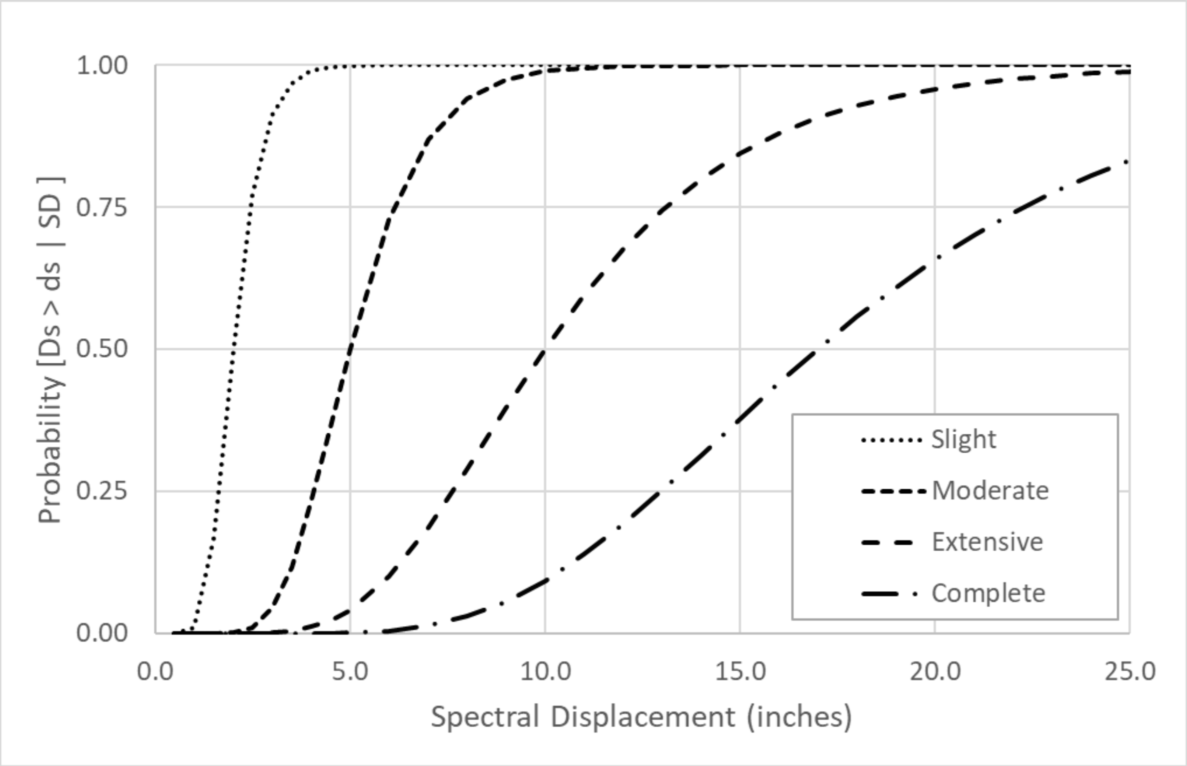


Figure 6-1 Example Fragility Curves for Slight, Moderate, Extensive, and Complete Damage States

The fragility curves are driven by a PEH parameter. For ground failure, the PEH parameter used to drive building fragility curves is PGD. For ground shaking, the PEH parameter used to drive building fragility curves is peak spectral response (either displacement or acceleration), or PGA for essential transportation and utility system facilities. Peak spectral response varies significantly for buildings that have different response properties and will, therefore, require knowledge of these properties.

Building response is characterized by building capacity curves. These curves describe the push-over displacement of each building type and seismic design level as a function of laterally-applied earthquake load. Design, yield, and ultimate capacity points define the shape of each building capacity curve. The methodology estimates peak building response as the intersection of the building capacity curve and the demand spectrum at the building's location.

The demand spectrum is the 5%-damped PEH input spectrum reduced for higher levels of effective damping (e.g., effective damping includes both elastic damping and hysteretic damping associated with post-yield cyclic response of the building). Figure 6-2 illustrates the intersection of a typical building capacity curve and a typical demand spectrum (reduced for effective damping greater than 5% of critical).

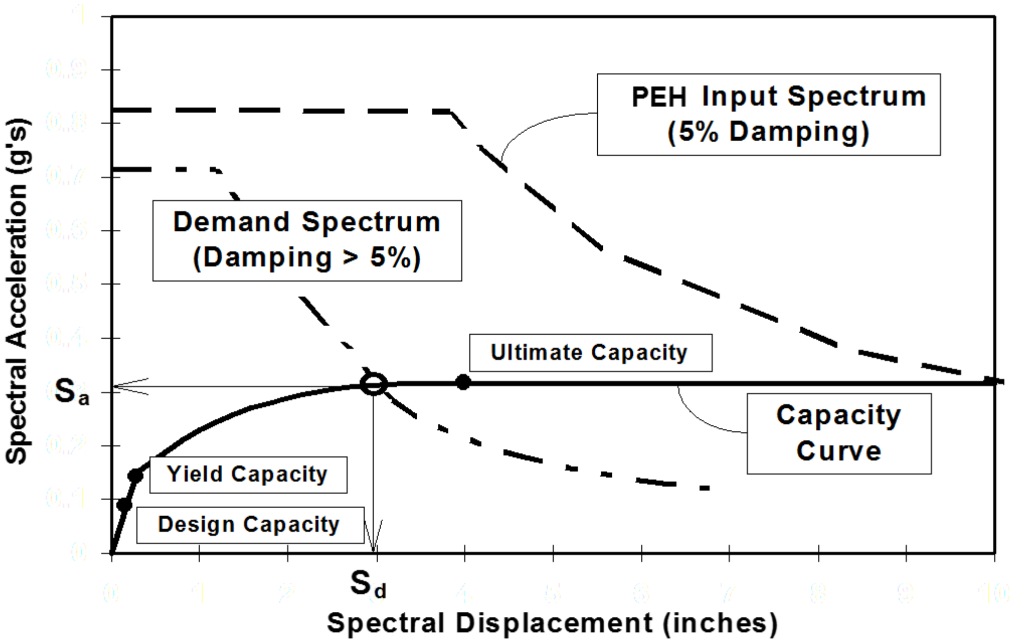


Figure 6-2 Example Building Capacity Curve and Demand Spectrum

6.4 Description of Specific Building Types and Building Damage States

The specific building types used for essential facilities are identical to those used for the general building stock (see Section 5.3). Typical nonstructural components of essential facilities include those architectural, mechanical and electrical, and contents listed in Table 5-2 for the general building stock.

Essential facilities also include certain special equipment, such as emergency generators, and certain special contents, such as those used to operate a hospital. Special equipment and contents of essential facilities are considered to be acceleration-sensitive nonstructural components of these facilities.

Building damage states for structural and nonstructural components of essential facilities are the same as those described in Section 5.3.3 for the general building stock.

6.5 Building Damage Due to Ground Shaking – Special Buildings

This section describes capacity and fragility curves used in the methodology to estimate the probability of Slight, Moderate, Extensive, and Complete damage to Special buildings of a given specific building type designed to High-, Moderate-, or Low-Code seismic standards. Special building damage functions are appropriate for evaluation of essential facilities when the user anticipates above-Code seismic performance for these facilities.

Capacity curves and fragility curves for Special buildings of High-Code, Moderate-Code, or Low-Code seismic design are based on modern code (e.g., 1976 Uniform Building *Code*, 1996 *NEHRP Provisions*, or later editions of these model codes) design criteria for various seismic design zones, as shown in Table 6-2. Additional description of seismic design levels may be found in Section 6.9). These Special building design levels are abbreviated HS, MS, and LS when used in the Hazus building inventories.

Table 6-2 Approximate Basis for Seismic Design Levels for Special Buildings

Seismic Design Level (I = 1.5)	Seismic Zone (1994 *Uniform Building Code*)	Map Area
Special High-Code (HS)	4	7
Special Moderate-Code (MS)	2B	5
Special Low-Code (LS)	1	3

The capacity and fragility curves represent buildings designed and constructed to modern seismic code provisions (e.g., 1994 UBC) using an importance factor of I = 1.5. Moderate-Code and Low-Code seismic design levels are included for completeness. Most essential facilities located in areas outside the Seismic Zones identified in Table 6-2 have not been designed for Special building code criteria.

6.5.1 Capacity Curves – Special Buildings

The building capacity curves for Special buildings are similar to those for the general building stock in Section 5.4.1, but with increased strength. Each curve is described by three control points that define model building capacity:

- Design Capacity
- Yield Capacity
- Ultimate Capacity

Design capacity represents the nominal building strength required by model seismic code provisions (e.g., 1994 *UBC* or later editions) including an importance factor of I = 1.5. Wind design is not considered in the estimation of design capacity and certain buildings (e.g., taller buildings located in zones of low or moderate seismicity) may have a lateral design strength considerably greater than nominal building strength based on seismic code provisions indicates.

Yield capacity represents the true lateral strength of the building considering redundancies in design, conservatism in code requirements, and true (rather than nominal) strength of materials. Ultimate capacity represents the maximum strength of the building when the global structural system has reached a fully plastic state. An example building capacity curve is shown in Figure 6-3.

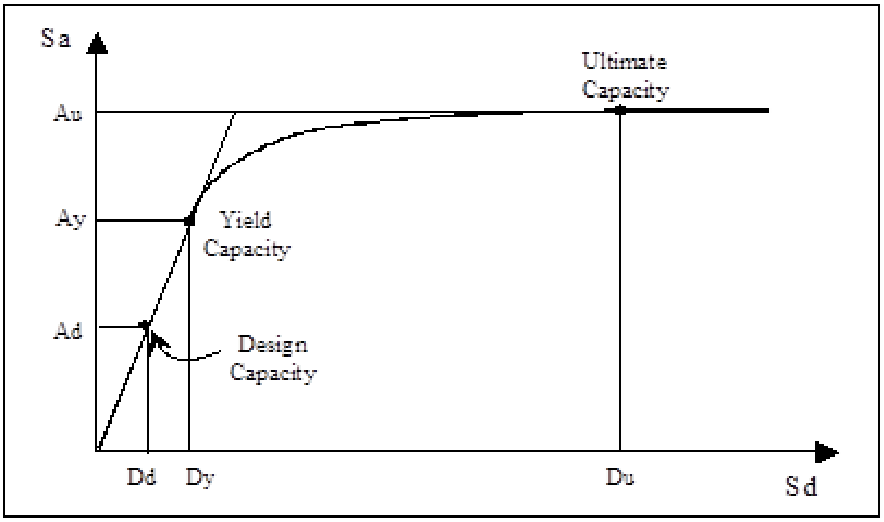


Figure 6-3 Example Building Capacity Curve

The building capacity curves for Special buildings are constructed based on the same engineering properties (i.e., T_e, α_1, α_2, γ, λ) as those used to describe capacity curves of Code buildings (i.e., Table 5-4, Table 5-5, Table 5-6 except for design strength, C_s, and ductility, μ). The design strength, C_s, is approximately based on the lateral force design requirements of seismic codes (e.g., 1994 *NEHRP* or 1994 *UBC*) using an importance factor of I = 1.5. Values of the "ductility" factor, D_u, for Special buildings are based on Code building ductility increased by a factor of 1.33 for Moderate-Code buildings and by a factor of 1.2 for Low-Code buildings. The ductility parameter defines the displacement value of the capacity curve at the point where the curve reaches a fully plastic state.

Building capacity curves are assumed to have a range of possible properties that are lognormally distributed as a function of the ultimate strength (Au) of each capacity curve. Special building capacity curves represent median estimates of building capacity. The variability of the capacity of each building type is assumed to be: $\beta(Au) = 0.15$ for Special buildings. An example construction of median, 84th percentile (+1β) and 16th percentile (-1β) building capacity curves for a typical building is illustrated in Figure 6-4. Median capacity curves are intersected with demand spectra to estimate peak building response. The variability of the capacity curves is used, with other sources of variability and uncertainty, to define total fragility curve variability.

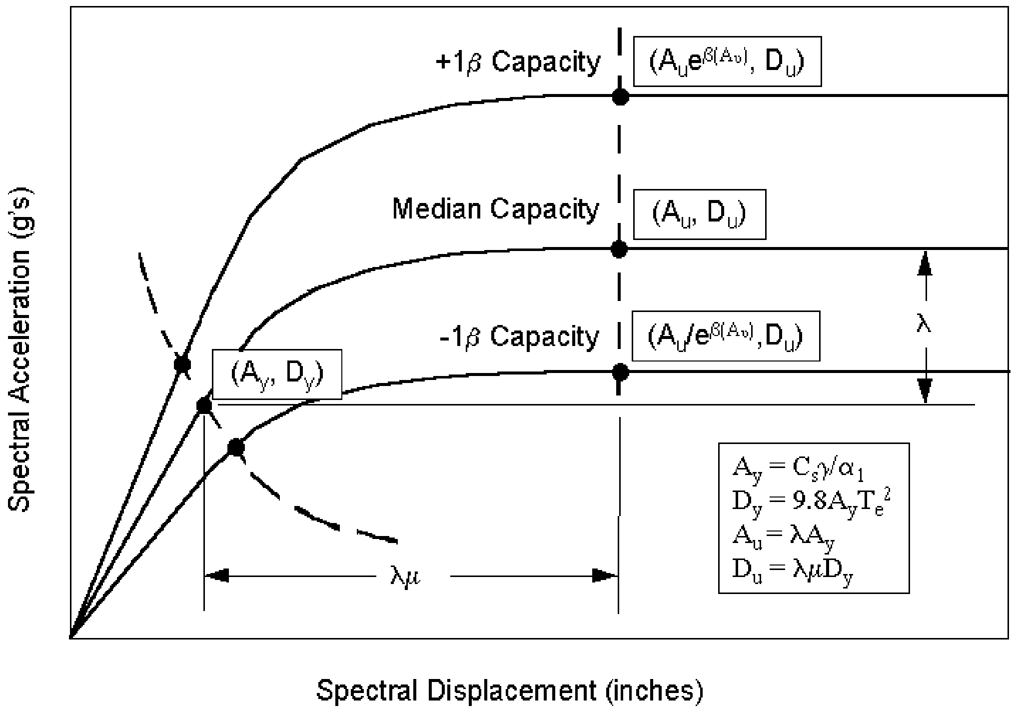


Figure 6-4 Example Construction of Median, +1β and -1β, Building Capacity Curves

Table 6-3, Table 6-4, and Table 6-5 summarize yield capacity and ultimate capacity control points for Special buildings of High-Code, Moderate-Code, and Low-Code seismic design levels, abbreviated HS, MS, and LS, respectively. Note that for the following tables, shaded boxes indicate types that are not permitted by current seismic codes.

Table 6-3 Special Building Capacity Curves – High-Code (High Special-HS) Seismic Design Level

Building Type	Yield Capacity Point		Ultimate Capacity Point	
	D_y (in.)	A_y (g)	D_u (in.)	A_u (g)
W1	0.72	0.600	17.27	1.800
W2	0.94	0.600	18.79	1.500
S1L	0.92	0.375	22.00	1.124
S1M	2.66	0.234	42.60	0.702
S1H	6.99	0.147	83.83	0.440
S2L	0.94	0.600	15.03	1.200
S2M	3.64	0.500	38.82	1.000
S2H	11.62	0.381	92.95	0.762
S3	0.94	0.600	15.03	1.200
S4L	0.58	0.480	10.36	1.080
S4M	1.64	0.400	19.65	0.900
S4H	5.23	0.305	47.05	0.685
S5L*	0.180*	0.150*	2.158*	0.300*
S5M*	0.512*	0.125*	4.094*	0.250*
S5H*	1.634	0.095*	9.803*	0.190*
C1L	0.59	0.375	14.08	1.124
C1M	1.73	0.312	27.65	0.937
C1H	3.02	0.147	36.20	0.440

Building Type	Yield Capacity Point		Ultimate Capacity Point	
	D_y (in.)	A_y (g)	D_u (in.)	A_u (g)
C2L	0.72	0.600	14.39	1.500
C2M	1.56	0.500	20.76	1.250
C2H	4.41	0.381	44.09	0.952
C3L*	0.180*	0.15*	2.428*	0.338*
C3M*	0.389*	0.125*	3.504*	0.281*
C3H*	1.102*	0.095*	7.440*	0.214*
PC1	1.08	0.900	17.27	1.800
PC2L	0.72	0.600	11.51	1.200
PC2M	1.56	0.500	16.61	1.000
PC2H	4.41	0.381	35.27	0.762
RM1L	0.96	0.800	15.34	1.600
RM1M	2.08	0.667	22.14	1.333
RM2L	0.96	0.800	15.34	1.600
RM2M	2.08	0.667	22.14	1.333
RM2H	5.88	0.508	47.02	1.015
URML*	0.360*	0.300*	4.315*	0.600*
URMM*	0.408*	0.167*	3.262*	0.333*
MH	0.27	0.225	4.32	0.450

** Shaded boxes and building types with an asterisk (*) indicate types that are not permitted by current seismic codes*

Table 6-4 Special Building Capacity Curves – Moderate-Code (Moderate Special- MS) Seismic Design Level

Building Type	Yield Capacity Point		Ultimate Capacity Point	
	D_y (in.)	A_y (g)	D_u (in.)	A_u (g)
W1	0.54	0.450	12.95	1.350
W2	0.47	0.300	9.40	0.750
S1L	0.46	0.187	11.00	0.562
S1M	1.33	0.117	21.30	0.351
S1H	3.49	0.073	41.91	0.220
S2L	0.47	0.300	7.52	0.600
S2M	1.82	0.250	19.41	0.500
S2H	5.81	0.190	46.47	0.381
S3	0.47	0.300	7.52	0.600
S4L	0.29	0.240	5.18	0.540
S4M	0.82	0.200	9.83	0.450
S4H	2.61	0.152	23.53	0.343
S5L*	0.180*	0.150*	2.158*	0.300*
S5M*	0.512*	0.125*	4.094*	0.250*
S5H*	1.634*	0.095*	9.803*	0.190*
C1L	0.29	0.187	7.04	0.562
C1M	0.86	0.156	13.83	0.468
C1H	1.51	0.073	18.10	0.220
C2L	0.36	0.300	7.19	0.750

Building Type	Yield Capacity Point		Ultimate Capacity Point	
	D_y (in.)	A_y (g)	D_u (in.)	A_u (g)
C2M	0.78	0.250	10.38	0.625
C2H	2.21	0.190	22.05	0.476
C3L*	0.180*	0.150*	2.428*	0.338*
C3M*	0.389*	0.125*	3.504*	0.281*
C3H*	1.102*	0.095*	7.440*	0.214*
PC1	0.54	0.450	8.63	0.900
PC2L	0.36	0.300	5.76	0.600
PC2M	0.78	0.250	8.31	0.500
PC2H	2.21	0.190	17.64	0.381
RM1L	0.48	0.400	7.67	0.800
RM1M	1.04	0.333	11.07	0.667
RM2L	0.48	0.400	7.67	0.800
RM2M	1.04	0.333	11.07	0.667
RM2H	2.94	0.254	23.51	0.508
URML*	0.360*	0.300*	4.315*	0.600*
URMM*	0.408*	0.167*	3.262*	0.333*
MH	0.27	0.225	4.32	0.450

** Shaded boxes and building types with an asterisk (*) indicate types that are not permitted by current seismic codes*

Table 6-5 Special Building Capacity Curves – Low-Code (Low Special-LS) Seismic Design Level

Building Type	Yield Capacity Point		Ultimate Capacity Point	
	D_y (in.)	A_y (g)	D_u (in.)	A_u (g)
W1	0.36	0.300	6.48	0.900
W2	0.24	0.150	3.52	0.375
S1L	0.23	0.094	4.13	0.281
S1M	0.67	0.059	7.99	0.176
S1H	1.75	0.037	15.72	0.110
S2L	0.24	0.150	2.82	0.300
S2M	0.91	0.125	7.28	0.250
S2H	2.91	0.095	17.43	0.190
S3	0.24	0.150	2.82	0.300
S4L	0.14	0.120	1.94	0.270
S4M	0.41	0.100	3.69	0.225
S4H	1.31	0.076	8.82	0.171
S5L	0.18	0.150	2.16	0.300
S5M	0.51	0.125	4.09	0.250
S5H	1.63	0.095	9.80	0.190
C1L	0.15	0.094	2.64	0.281
C1M	0.43	0.078	5.19	0.234
C1H	0.75	0.037	6.79	0.110
C2L	0.18	0.150	2.70	0.375
C2M	0.39	0.125	3.89	0.313
C2H	1.10	0.095	8.27	0.238

Building Type	Yield Capacity Point		Ultimate Capacity Point	
	D_y (in.)	A_y (g)	D_u (in.)	A_u (g)
C3L	0.18	0.150	2.43	0.338
C3M	0.39	0.125	3.50	0.281
C3H	1.10	0.095	7.44	0.214
PC1	0.27	0.225	3.24	0.450
PC2L	0.18	0.150	2.16	0.300
PC2M	0.39	0.125	3.11	0.250
PC2H	1.10	0.095	6.61	0.190
RM1L	0.24	0.200	2.88	0.400
RM1M	0.52	0.167	4.15	0.333
RM2L	0.24	0.200	2.88	0.400
RM2M	0.52	0.167	4.15	0.333
RM2H	1.47	0.127	8.82	0.254
URML	0.36	0.300	4.32	0.600
URMM	0.41	0.167	3.26	0.333
MH	0.27	0.225	4.32	0.450

6.5.2 Fragility Curves – Special Buildings

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

Special building fragility curves for ground failure are the same as those of Code buildings (Section 5.4.2).

6.5.2.1 Background

The form of the fragility curves for Special buildings is the same as that used for Code buildings. The probability of being in, or exceeding, a given damage state is modeled as a cumulative lognormal distribution. Given the appropriate PEH parameter (e.g., spectral displacement, Sd, for structural damage), the probability of being in or exceeding a damage state, ds, is modeled as follows:

Equation 6-1

$$P[ds|S_d] = \Phi\left[\frac{1}{\beta_{ds}} \ln\left(\frac{S_d}{\bar{S}_{s,ds}}\right)\right]$$

Where:

$\bar{S}_{d,ds}$	is the median value of spectral displacement at which the building reaches the threshold of the damage state, ds
β_{ds}	is the standard deviation of the natural logarithm of spectral displacement for damage state, ds

Φ is the standard normal cumulative distribution function.

6.5.2.2 Structural Damage – Special Buildings

Structural damage states for Special buildings are based on drift ratios that are assumed to be slightly higher than those of Code buildings of the same specific building type and seismic design level. It is difficult to quantify this improvement in displacement capacity since it is a function not just of building type and design parameters, but also design review and construction inspection. It is assumed that the improvement in displacement capacity results in an increase by a factor of 1.25 in drift capacity of each damage state for all Special building types and seismic design levels. Special buildings perform better than Code buildings due to increased structural strength (reflected in the capacity curves) and increased displacement capacity (reflected in the fragility curves). In general, increased strength tends to best improve building performance near yield and improved displacement capacity tends to best improve the ultimate capacity of the building.

Median values of Special building structural fragility are based on drift ratios (that describe the threshold of damage states and the height of the building to point of push-over mode displacement) using the same approach as that of Code buildings (Section 5.4.2.4).

The variability of Special building structural damage is based on the same approach as that of Code buildings. The total variability of each structural damage state, β_{Sds} , is modeled by the combination of following three contributors to damage variability:

- Uncertainty in the damage state threshold of the structural system: $\beta_{M(Sds)} = 0.4$, for all structural damage states and building types.
- Variability in capacity (response) properties of the specific building type/seismic design level of interest: $\beta_{C(Au)} = 0.15$ for Special buildings.
- Variability in response due to the spatial variability of ground motion demand: $\beta_{D(A)} = 0.45$ and $\beta_{C(V)} = 0.50$ is based on the dispersion factor typical of the attenuation of large-magnitude earthquakes as in the WUS (Section 4).

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

Table 6-6, Table 6-7, and Table 6-8 summarize median and lognormal standard deviation (β_{Sds}) values for Slight, Moderate, Extensive, and Complete structural damage states of Special buildings for High-Code, Moderate-Code, and Low-Code seismic design levels, HS, MS, and LS, respectively. Note that for the following tables, shaded boxes indicate types that are not permitted by current seismic codes.

Table 6-6 Building Structural Fragility – High-Code (High Special-HS) Seismic Design Level

Building Properties			Inter-Story Drift at Threshold of Damage State				Spectral Displacement (Inches)							
Type	Height (Inches)						Slight		Moderate		Extensive		Complete	
	Roof	Modal	Slight	Moderate	Extensive	Complete	Median	Beta	Median	Beta	Median	Beta	Median	Beta
W1	168	126	0.0050	0.0150	0.0500	0.1250	0.63	0.66	1.89	0.72	6.30	0.72	15.75	0.91
W2	288	216	0.0050	0.0150	0.0500	0.1250	1.08	0.69	3.24	0.77	10.80	0.89	27.00	0.85
S1L	288	216	0.0075	0.0150	0.0375	0.1000	1.62	0.67	3.24	0.70	8.10	0.71	21.60	0.68
S1M	720	540	0.0050	0.0100	0.0250	0.0667	2.70	0.62	5.40	0.62	13.50	0.63	36.00	0.71
S1H	1,872	1,123	0.0037	0.0075	0.0188	0.0500	4.21	0.63	8.42	0.62	21.06	0.62	56.16	0.63
S2L	288	216	0.0063	0.0125	0.0375	0.1000	1.35	0.69	2.70	0.80	8.10	0.89	21.60	0.84
S2M	720	540	0.0042	0.0083	0.0250	0.0667	2.25	0.62	4.50	0.66	13.50	0.66	36.00	0.71
S2H	1,872	1,123	0.0031	0.0063	0.0188	0.0500	3.51	0.62	7.02	0.63	21.06	0.63	56.16	0.66
S3	180	135	0.0050	0.0100	0.0300	0.0875	0.68	0.66	1.35	0.71	4.05	0.80	11.81	0.90
S4L	288	216	0.0050	0.0100	0.0300	0.0875	1.08	0.77	2.16	0.82	6.48	0.92	18.90	0.91
S4M	720	540	0.0033	0.0067	0.0200	0.0583	1.80	0.69	3.60	0.67	10.80	0.68	31.50	0.82
S4H	1,872	1,123	0.0025	0.0050	0.0150	0.0438	2.81	0.62	5.62	0.63	16.85	0.65	49.14	0.73
S5L*														
S5M*														
S5H*														
C1L	240	180	0.0063	0.0125	0.0375	0.1000	1.13	0.69	2.25	0.74	6.75	0.82	18.00	0.81
C1M	600	450	0.0042	0.0083	0.0250	0.0667	1.87	0.63	3.75	0.65	11.25	0.66	30.00	0.71
C1H	1,440	864	0.0031	0.0063	0.0188	0.0500	2.70	0.63	5.40	0.63	16.20	0.63	43.20	0.69
C2L	240	180	0.0050	0.0125	0.0375	0.1000	0.90	0.69	2.25	0.72	6.75	0.82	18.00	0.95
C2M	600	450	0.0033	0.0083	0.0250	0.0667	1.50	0.65	3.75	0.69	11.25	0.66	30.00	0.70
C2H	14,40	864	0.0025	0.0063	0.0188	0.0500	2.16	0.62	5.40	0.63	16.20	0.64	43.20	0.69
C3L*														
C3M*														
C3H*														

Building Properties			Inter-Story Drift at Threshold of Damage State				Spectral Displacement (Inches)							
Type	Height (Inches)						Slight		Moderate		Extensive		Complete	
	Roof	Modal	Slight	Moderate	Extensive	Complete	Median	Beta	Median	Beta	Median	Beta	Median	Beta
PC1	180	135	0.0050	0.0100	0.0300	0.0875	0.68	0.63	1.35	0.74	4.05	0.79	11.81	0.96
PC2L	240	180	0.0050	0.0100	0.0300	0.0875	0.90	0.76	1.80	0.80	5.40	0.87	15.75	0.97
PC2M	600	450	0.0033	0.0067	0.0200	0.0583	1.50	0.66	3.00	0.73	9.00	0.72	26.25	0.73
PC2H	1,440	864	0.0025	0.0050	0.0150	0.0438	2.16	0.62	4.32	0.64	12.95	0.65	37.80	0.74
RM1L	240	180	0.0050	0.0100	0.0300	0.0875	0.90	0.70	1.80	0.74	5.40	0.76	15.75	0.98
RM1M	600	450	0.0033	0.0067	0.0200	0.0583	1.50	0.63	3.00	0.68	9.00	0.70	26.25	0.70
RM2L	240	180	0.0050	0.0100	0.0300	0.0875	0.90	0.66	1.80	0.70	5.40	0.76	15.75	0.97
RM2M	600	450	0.0033	0.0067	0.0200	0.0583	1.50	0.63	3.00	0.70	9.00	0.70	26.25	0.70
RM2H	1,440	864	0.0025	0.0050	0.0150	0.0438	2.16	0.63	4.32	0.63	12.96	0.63	37.80	0.65
URML*														
URMM*														
MH	120	120	0.0050	0.0100	0.0300	0.0875	0.60	0.81	1.20	0.89	3.60	0.97	10.50	0.86

**Shaded boxes and building types with an asterisk (*) indicate types that are not permitted by current seismic codes.*

Table 6-7 Building Structural Fragility – Moderate-Code (Moderate Special-MS) Seismic Design Level

Building Properties			Inter-Story Drift at Threshold of Damage State				Spectral Displacement (Inches)							
Type	Height (Inches)						Slight		Moderate		Extensive		Complete	
	Roof	Modal	Slight	Moderate	Extensive	Complete	Median	Beta	Median	Beta	Median	Beta	Median	Beta
W1	168	126	0.0050	0.0124	0.0383	0.0937	0.63	0.76	1.56	0.77	4.82	0.78	11.81	0.96
W2	288	216	0.0050	0.0124	0.0383	0.0938	1.08	0.79	2.68	0.86	8.27	0.88	20.25	0.84
S1L	288	216	0.0075	0.0130	0.0294	0.0750	1.62	0.73	2.80	0.71	6.35	0.70	16.20	0.77
S1M	720	540	0.0050	0.0086	0.0196	0.0500	2.70	0.64	4.67	0.65	10.58	0.66	27.00	0.75
S1H	1,872	1,123	0.0037	0.0065	0.0147	0.0375	4.21	0.62	7.29	0.62	16.51	0.66	42.12	0.70
S2L	288	216	0.0063	0.0108	0.0292	0.0750	1.35	0.82	2.34	0.85	6.30	0.89	16.20	0.85
S2M	720	540	0.0042	0.0072	0.0194	0.0500	2.25	0.66	3.90	0.66	10.50	0.68	27.00	0.81
S2H	1,872	1,123	0.0031	0.0054	0.0146	0.0375	3.51	0.62	6.08	0.63	16.38	0.65	42.12	0.71

Building Properties			Inter-Story Drift at Threshold of Damage State				Spectral Displacement (Inches)							
Type	Height (Inches)						Slight		Moderate		Extensive		Complete	
	Roof	Modal	Slight	Moderate	Extensive	Complete	Median	Beta	Median	Beta	Median	Beta	Median	Beta
S3	180	135	0.0050	0.0087	0.0234	0.0656	0.68	0.77	1.17	0.81	3.16	0.89	8.86	0.89
S4L	288	216	0.0050	0.0087	0.0234	0.0656	1.08	0.88	1.87	0.92	5.05	0.98	14.18	0.87
S4M	720	540	0.0033	0.0058	0.0156	0.0437	1.80	0.70	3.12	0.67	8.41	0.70	23.62	0.90
S4H	1,872	1,123	0.0025	0.0043	0.0117	0.0328	2.81	0.66	4.87	0.66	13.13	0.70	36.86	0.81
S5L*														
S5M*														
S5H*														
C1L	240	180	0.0063	0.0108	0.0292	0.0750	1.13	0.80	1.95	0.82	5.25	0.84	13.50	0.81
C1M	600	450	0.0042	0.0072	0.0194	0.0500	1.87	0.66	3.25	0.67	8.75	0.66	22.50	0.84
C1H	1,440	864	0.0031	0.0054	0.0146	0.0375	2.70	0.64	4.68	0.64	12.60	0.68	32.40	0.81
C2L	240	180	0.0050	0.0105	0.0289	0.0750	0.90	0.77	1.89	0.86	5.21	0.91	13.50	0.89
C2M	600	450	0.0033	0.0070	0.0193	0.0500	1.50	0.71	3.16	0.70	8.68	0.69	22.50	0.83
C2H	1,440	864	0.0025	0.0053	0.0145	0.0375	2.16	0.64	4.55	0.65	12.51	0.66	32.40	0.79
C3L*														
C3M*														
C3H*														
PC1	180	135	0.0050	0.0087	0.0234	0.0656	0.68	0.79	1.17	0.81	3.16	0.86	8.86	1.00
PC2L	240	180	0.0050	0.0087	0.0234	0.0656	0.90	0.83	1.56	0.89	4.21	0.97	11.81	0.89
PC2M	600	450	0.0033	0.0058	0.0156	0.0438	1.50	0.76	2.60	0.74	7.01	0.73	19.69	0.88
PC2H	1,440	864	0.0025	0.0043	0.0117	0.0328	2.16	0.65	3.75	0.66	10.10	0.70	28.35	0.81
RM1L	240	180	0.0050	0.0087	0.0234	0.0656	0.90	0.80	1.56	0.85	4.21	0.92	11.81	0.97
RM1M	600	450	0.0033	0.0058	0.0156	0.0438	1.50	0.73	2.60	0.75	7.01	0.75	19.69	0.80
RM2L	240	180	0.0050	0.0087	0.0234	0.0656	0.90	0.77	1.56	0.81	4.21	0.92	11.81	0.96
RM2M	600	450	0.0033	0.0058	0.0156	0.0438	1.50	0.72	2.60	0.72	7.01	0.72	19.69	0.77
RM2H	1,440	864	0.0025	0.0043	0.0117	0.0328	2.16	0.63	3.75	0.65	10.10	0.66	28.35	0.76
URML*														

Building Properties			Inter-Story Drift at Threshold of Damage State				Spectral Displacement (Inches)							
Type	Height (Inches)						Slight		Moderate		Extensive		Complete	
	Roof	Modal	Slight	Moderate	Extensive	Complete	Median	Beta	Median	Beta	Median	Beta	Median	Beta
URMM*														
MH	120	120	0.0050	0.0100	0.0300	0.0875	0.60	0.81	1.20	0.89	3.60	0.97	10.50	0.86

**Shaded boxes and building types with an asterisk (*) indicate types that are not permitted by current seismic codes.*

Table 6-8 Special Building Structural Fragility – Low-Code (Low Special-LS) Seismic Design Level

Building Properties			Inter-Story Drift at Threshold of Damage State				Spectral Displacement (Inches)							
Type	Height (Inches)						Slight		Moderate		Extensive		Complete	
	Roof	Modal	Slight	Moderate	Extensive	Complete	Median	Beta	Median	Beta	Median	Beta	Median	Beta
W1	168	126	0.0050	0.0124	0.0383	0.0937	0.63	0.80	1.56	0.81	4.82	0.88	11.81	1.01
W2	288	216	0.0050	0.0124	0.0383	0.0938	1.08	0.89	2.68	0.89	8.27	0.86	20.25	0.97
S1L	288	216	0.0075	0.0119	0.0253	0.0625	1.62	0.73	2.58	0.73	5.47	0.75	13.50	0.93
S1M	720	540	0.0050	0.0080	0.0169	0.0417	2.70	0.66	4.30	0.70	9.12	0.78	22.50	0.91
S1H	1,872	1,123	0.0037	0.0060	0.0127	0.0313	4.21	0.64	6.72	0.66	14.23	0.68	35.10	0.86
S2L	288	216	0.0063	0.0100	0.0250	0.0625	1.35	0.89	2.16	0.89	5.40	0.88	13.50	0.97
S2M	720	540	0.0042	0.0067	0.0167	0.0417	2.25	0.67	3.60	0.68	9.00	0.74	22.50	0.92
S2H	1,872	1,123	0.0031	0.0050	0.0125	0.0313	3.51	0.62	5.62	0.63	14.04	0.68	35.10	0.84
S3	180	135	0.0050	0.0080	0.0201	0.0547	0.68	0.89	1.08	0.90	2.71	0.98	7.38	0.85
S4L	288	216	0.0050	0.0080	0.0200	0.0547	1.08	0.98	1.73	0.95	4.33	0.97	11.81	0.98
S4M	720	540	0.0033	0.0053	0.0134	0.0364	1.80	0.69	2.88	0.72	7.22	0.81	19.68	0.98
S4H	1,872	1,123	0.0025	0.0040	0.0100	0.0273	2.81	0.66	4.50	0.67	11.26	0.78	30.71	0.93
S5L	288	216	0.0038	0.0075	0.0188	0.0438	0.81	1.00	1.62	1.00	4.05	1.03	9.45	0.91
S5M	720	540	0.0025	0.0050	0.0125	0.0292	1.35	0.74	2.70	0.72	6.75	0.78	15.75	0.94
S5H	1,872	1,123	0.0019	0.0037	0.0094	0.0219	2.11	0.67	4.21	0.69	10.53	0.74	24.57	0.90
C1L	240	180	0.0063	0.0100	0.0250	0.0625	1.13	0.85	1.80	0.85	4.50	0.88	11.25	0.95
C1M	600	450	0.0042	0.0067	0.0167	0.0417	1.87	0.70	3.00	0.69	7.50	0.75	18.75	0.95
C1H	1,440	864	0.0031	0.0050	0.0125	0.0313	2.70	0.66	4.32	0.71	10.80	0.79	27.00	0.95

Building Properties			Inter-Story Drift at Threshold of Damage State				Spectral Displacement (Inches)							
Type	Height (Inches)						Slight		Moderate		Extensive		Complete	
	Roof	Modal	Slight	Moderate	Extensive	Complete	Median	Beta	Median	Beta	Median	Beta	Median	Beta
C2L	240	180	0.0050	0.0096	0.0247	0.0625	0.90	0.91	1.72	0.94	4.44	1.01	11.25	0.90
C2M	600	450	0.0033	0.0064	0.0164	0.0417	1.50	0.76	2.86	0.74	7.40	0.74	18.75	0.94
C2H	1,440	864	0.0025	0.0048	0.0123	0.0313	2.16	0.66	4.12	0.67	10.66	0.74	27.00	0.91
C3L	240	180	0.0038	0.0075	0.0188	0.0438	0.68	0.92	1.35	0.99	3.38	1.04	7.88	0.88
C3M	600	450	0.0025	0.0050	0.0125	0.0292	1.12	0.77	2.25	0.79	5.62	0.78	13.12	0.93
C3H	1,440	864	0.0019	0.0038	0.0094	0.0219	1.62	0.68	3.24	0.69	8.10	0.70	18.90	0.88
PC1	180	135	0.0050	0.0080	0.0201	0.0547	0.68	0.89	1.08	0.95	2.71	1.00	7.38	0.96
PC2L	240	180	0.0050	0.0080	0.0201	0.0547	0.90	0.98	1.44	0.98	3.61	1.02	9.84	0.91
PC2M	600	450	0.0033	0.0053	0.0134	0.0364	1.50	0.76	2.40	0.75	6.02	0.75	16.40	0.94
PC2H	1,440	864	0.0025	0.0040	0.0100	0.0273	2.16	0.66	3.46	0.68	8.66	0.73	23.63	0.92
RM1L	240	180	0.0050	0.0080	0.0201	0.0547	0.90	0.97	1.44	1.01	3.61	1.07	9.84	0.88
RM1M	600	450	0.0033	0.0053	0.0134	0.0364	1.50	0.78	2.40	0.78	6.02	0.78	16.40	0.94
RM2L	240	180	0.0050	0.0080	0.0201	0.0547	0.90	0.94	1.44	0.98	3.61	1.05	9.84	0.89
RM2M	600	450	0.0033	0.0053	0.0134	0.0364	1.50	0.76	2.40	0.75	6.02	0.75	16.40	0.92
RM2H	1,440	864	0.0025	0.0040	0.0100	0.0273	2.16	0.66	3.46	0.67	8.66	0.80	23.63	0.89
URML	180	135	0.0038	0.0075	0.0187	0.0438	0.51	0.89	1.01	0.91	2.53	0.96	5.91	1.09
URMM	420	315	0.0025	0.0050	0.0125	0.0292	0.79	0.81	1.57	0.84	3.94	0.87	9.19	0.82
MH	120	120	0.0050	0.0100	0.0300	0.0875	0.60	0.81	1.20	0.89	3.60	0.97	10.50	0.86

6.5.2.3 Nonstructural Damage – Drift-Sensitive

Damage states of nonstructural drift-sensitive components of Special buildings are based on the same drift ratios as those of Code buildings. Even for essential facilities, nonstructural components are typically not designed or detailed for special earthquake displacements. Improvement in the performance of drift-sensitive components of Special buildings is assumed to be entirely a function of drift reduction due to the increased stiffness and strength of the structures of these buildings.

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

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

- Uncertainty in the damage state threshold of nonstructural components: $\beta_{\mathrm{M(NSDds)}}$ = 0.5 for all structural damage states and building types
- Variability in capacity (response) properties of the specific building type that contains the nonstructural components of interest: $\beta_{\mathrm{C(Au)}}$ = 0.15 for Special buildings
- Variability in response of the specific building type due to the spatial variability of ground motion demand: $\beta_{\mathrm{D(A)}}$ = 0.45 and $\beta_{\mathrm{C(V)}}$ = 0.50

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

Table 6-9, Table 6-10, and Table 6-11 summarize median and lognormal standard deviation (β_{NSDds}) values for Slight, Moderate, Extensive, and Complete damage states of nonstructural drift-sensitive components of Special buildings for High-Code, Moderate-Code, and Low-Code seismic design levels, HS, MS, and LS, respectively.

Table 6-9 Special Building Nonstructural Drift-Sensitive Fragility – High-Code (High Special-HS) Seismic Design Level

BUILDING TYPE	MEDIAN SPECTRAL DISPLACEMENT (INCHES) AND LOGSTANDARD DEVIATION							
	Slight		Moderate		Extensive		Complete	
	Median	Beta	Median	Beta	Median	Beta	Median	Beta
W1	0.50	0.74	1.01	0.77	3.15	0.79	6.30	0.78
W2	0.86	0.76	1.73	0.77	5.40	0.88	10.80	0.93
S1L	0.86	0.72	1.73	0.76	5.40	0.75	10.80	0.74
S1M	2.16	0.68	4.32	0.68	13.50	0.70	27.00	0.73
S1H	4.49	0.70	8.99	0.69	28.08	0.69	56.16	0.70
S2L	0.86	0.74	1.73	0.77	5.40	0.90	10.80	0.95
S2M	2.16	0.70	4.32	0.72	13.50	0.73	27.00	0.72
S2H	4.49	0.71	8.99	0.69	28.08	0.70	56.16	0.73
S3	0.54	0.70	1.08	0.76	3.38	0.83	6.75	0.93
S4L	0.86	0.81	1.73	0.84	5.40	0.93	10.80	1.00
S4M	2.16	0.76	4.32	0.74	13.50	0.75	27.00	0.82
S4H	4.49	0.70	8.99	0.71	28.08	0.72	56.16	0.80
S5L*								
S5M*								
S5H*								
C1L	0.72	0.77	1.44	0.76	4.50	0.84	9.00	0.88
C1M	1.80	0.71	3.60	0.71	11.25	0.72	22.50	0.71
C1H	3.46	0.70	6.91	0.69	21.60	0.71	43.20	0.75
C2L	0.72	0.76	1.44	0.76	4.50	0.80	9.00	0.94
C2M	1.80	0.74	3.60	0.76	11.25	0.73	22.50	0.74
C2H	3.46	0.69	6.91	0.69	21.60	0.71	43.20	0.75
C3L*								
C3M*								
C3H*								
PC1	0.54	0.69	1.08	0.78	3.38	0.85	6.75	0.88
PC2L	0.72	0.80	1.44	0.83	4.50	0.90	9.00	1.03
PC2M	1.80	0.75	3.60	0.80	11.25	0.77	22.50	0.77
PC2H	3.46	0.70	6.91	0.71	21.60	0.73	43.20	0.82
RM1L	0.72	0.74	1.44	0.80	4.50	0.80	9.00	0.94
RM1M	1.80	0.70	3.60	0.77	11.25	0.77	22.50	0.77
RM2L	0.72	0.74	1.44	0.76	4.50	0.78	9.00	0.96
RM2M	1.80	0.71	3.60	0.78	11.25	0.74	22.50	0.74
RM2H	3.46	0.69	6.91	0.69	21.60	0.71	43.20	0.74
URML*								
URMM*								
MH	0.48	0.85	0.96	0.92	3.00	0.98	6.00	0.99

**Shaded boxes and building types with an asterisk (*) indicate types that are not permitted by current seismic codes.*

Table 6-10 Special Building Nonstructural Drift-Sensitive Fragility – Moderate-Code (Moderate Special-MS) Seismic Design Level

Building Type	Median Spectral Displacement (Inches) and Logstandard Deviation							
	Slight		Moderate		Extensive		Complete	
	Median	Beta	Median	Beta	Median	Beta	Median	Beta
W1	0.50	0.77	1.01	0.82	3.15	0.84	6.30	0.87
W2	0.86	0.84	1.73	0.88	5.40	0.93	10.80	0.93
S1L	0.86	0.78	1.73	0.78	5.40	0.78	10.80	0.76
S1M	2.16	0.71	4.32	0.71	13.50	0.73	27.00	0.81
S1H	4.49	0.69	8.99	0.69	28.08	0.72	56.16	0.82
S2L	0.86	0.81	1.73	0.91	5.40	0.96	10.80	0.89
S2M	2.16	0.73	4.32	0.74	13.50	0.73	27.00	0.87
S2H	4.49	0.69	8.99	0.70	28.08	0.74	56.16	0.84
S3	0.54	0.82	1.08	0.86	3.38	0.97	6.75	0.95
S4L	0.86	0.89	1.73	0.97	5.40	1.02	10.80	0.94
S4M	2.16	0.76	4.32	0.74	13.50	0.84	27.00	0.97
S4H	4.49	0.71	8.99	0.73	28.08	0.83	56.16	0.94
S5L*								
S5M*								
S5H*								
C1L	0.72	0.80	1.44	0.86	4.50	0.88	9.00	0.88
C1M	1.80	0.73	3.60	0.72	11.25	0.74	22.50	0.89
C1H	3.46	0.71	6.91	0.71	21.60	0.79	43.20	0.93
C2L	0.72	0.84	1.44	0.87	4.50	0.95	9.00	1.00
C2M	1.80	0.79	3.60	0.76	11.25	0.76	22.50	0.88
C2H	3.46	0.70	6.91	0.71	21.60	0.77	43.20	0.87
C3L*								
C3M*								
C3H*								
PC1	0.54	0.82	1.08	0.87	3.38	0.93	6.75	1.02
PC2L	0.72	0.88	1.44	0.95	4.50	1.03	9.00	0.99
PC2M	1.80	0.84	3.60	0.77	11.25	0.79	22.50	0.95
PC2H	3.46	0.72	6.91	0.74	21.60	0.84	43.20	0.94
RM1L	0.72	0.86	1.44	0.88	4.50	0.99	9.00	1.04
RM1M	1.80	0.80	3.60	0.79	11.25	0.79	22.50	0.88
RM2L	0.72	0.81	1.44	0.86	4.50	0.97	9.00	1.03
RM2M	1.80	0.78	3.60	0.77	11.25	0.77	22.50	0.88
RM2H	3.46	0.71	6.91	0.71	21.60	0.74	43.20	0.87
URML*								
URMM*								
MH	0.48	0.85	0.96	0.92	3.00	0.98	6.00	0.99

**Shaded boxes and building types with an asterisk (*) indicate types that are not permitted by current seismic codes.*

Table 6-11 Special Building Nonstructural Drift-Sensitive Fragility – Low-Code (Low Special-LS) Seismic Design Level

Building Type	Median Spectral Displacement (inches) and Logstandard Deviation (Beta)							
	Slight		Moderate		Extensive		Complete	
	Median	Beta	Median	Beta	Median	Beta	Median	Beta
W1	0.50	0.83	1.01	0.86	3.15	0.88	6.30	1.00
W2	0.86	0.93	1.73	0.94	5.40	0.99	10.80	0.93
S1L	0.86	0.81	1.73	0.80	5.40	0.80	10.80	0.94
S1M	2.16	0.73	4.32	0.76	13.50	0.86	27.00	0.98
S1H	4.49	0.71	8.99	0.74	28.08	0.87	56.16	0.98
S2L	0.86	0.94	1.73	0.93	5.40	0.93	10.80	0.98
S2M	2.16	0.73	4.32	0.76	13.50	0.91	27.00	0.99
S2H	4.49	0.71	8.99	0.74	28.08	0.85	56.16	0.96
S3	0.54	0.89	1.08	0.96	3.38	1.01	6.75	0.90
S4L	0.86	1.02	1.73	0.99	5.40	0.95	10.80	1.01
S4M	2.16	0.76	4.32	0.84	13.50	0.95	27.00	1.04
S4H	4.49	0.74	8.99	0.87	28.08	0.96	56.16	1.03
S5L	0.86	1.04	1.73	1.04	5.40	1.00	10.80	0.99
S5M	2.16	0.78	4.32	0.84	13.50	0.97	27.00	1.04
S5H	4.49	0.76	8.99	0.87	28.08	0.96	56.16	1.03
C1L	0.72	0.90	1.44	0.92	4.50	0.93	9.00	0.93
C1M	1.80	0.74	3.60	0.77	11.25	0.94	22.50	1.00
C1H	3.46	0.75	6.91	0.86	21.60	0.97	43.20	1.03
C2L	0.72	0.93	1.44	0.99	4.50	1.06	9.00	0.92
C2M	1.80	0.80	3.60	0.80	11.25	0.91	22.50	1.00
C2H	3.46	0.73	6.91	0.80	21.60	0.93	43.20	1.01
C3L	0.72	0.99	1.44	1.05	4.50	1.06	9.00	0.93
C3M	1.80	0.84	3.60	0.83	11.25	0.95	22.50	1.01
C3H	3.46	0.76	6.91	0.84	21.60	0.96	43.20	1.03
PC1	0.54	0.92	1.08	0.99	3.38	1.07	6.75	1.02
PC2L	0.72	0.99	1.44	1.02	4.50	1.02	9.00	0.95
PC2M	1.80	0.81	3.60	0.82	11.25	0.95	22.50	1.02
PC2H	3.46	0.74	6.91	0.86	21.60	0.96	43.20	1.02
RM1L	0.72	0.98	1.44	1.06	4.50	1.08	9.00	0.94
RM1M	1.80	0.83	3.60	0.84	11.25	0.91	22.50	0.99
RM2L	0.72	0.94	1.44	1.03	4.50	1.07	9.00	0.92
RM2M	1.80	0.81	3.60	0.80	11.25	0.91	22.50	0.99
RM2H	3.46	0.74	6.91	0.79	21.60	0.92	43.20	1.01
URML	0.54	0.93	1.08	0.98	3.38	1.05	6.75	1.11
URMM	1.26	0.89	2.52	0.88	7.88	0.87	15.75	0.99
MH	0.48	0.85	0.96	0.92	3.00	0.98	6.00	0.99

6.5.2.4 Nonstructural Damage – Acceleration-Sensitive Components

Damage states of nonstructural acceleration-sensitive components of Special buildings are based on the peak floor accelerations of Code buildings increased by a factor of 1.5. A factor of 1.5 on damage state acceleration reflects increased anchorage strength of nonstructural acceleration-sensitive components of Special buildings.

The floor acceleration values are used directly as median values, assuming average upper floor demand is represented by response at the point of the push-over mode displacement.

The total variability of each damage state (β_{NSAds}) is modeled by the combination of the following three contributors to nonstructural acceleration-sensitive damage variability:

- Uncertainty in the damage state threshold of nonstructural components: $\beta_{\mathrm{M(NSDds)}}$ = 0.6 for all structural damage states and building types
- Variability in capacity (response) properties of the specific building type that contains the nonstructural components of interest: $\beta_{\mathrm{C(Au)}}$ = 0.15 for Special buildings
- Variability in response of the specific building type due to the spatial variability of ground motion demand: $\beta_{\mathrm{D(A)}}$ = 0.45 and $\beta_{\mathrm{C(V)}}$ = 0.50

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

Table 6-12, Table 6-13, and Table 6-14 summarize median and lognormal standard deviation (β_{NSDds}) values for Slight, Moderate, Extensive, and Complete damage states of nonstructural drift-sensitive components of Special buildings for High-Code, Moderate-Code, and Low-Code seismic design levels, HS, MS, and LS, respectively.

Table 6-12 Special Building Nonstructural Acceleration-Sensitive Fragility - High-Code (High Special-HS) Seismic Design Level

Building Type	Median Spectral Acceleration (g) and Logstandard Deviation (Beta)							
	Slight		Moderate		Extensive		Complete	
	Median	Beta	Median	Beta	Median	Beta	Median	Beta
W1	0.45	0.72	0.90	0.68	1.80	0.68	3.60	0.68
W2	0.45	0.69	0.90	0.67	1.80	0.68	3.60	0.68
S1L	0.45	0.66	0.90	0.67	1.80	0.67	3.60	0.67
S1M	0.45	0.66	0.90	0.67	1.80	0.68	3.60	0.68
S1H	0.45	0.67	0.90	0.66	1.80	0.66	3.60	0.66
S2L	0.45	0.66	0.90	0.67	1.80	0.66	3.60	0.66
S2M	0.45	0.68	0.90	0.65	1.80	0.65	3.60	0.65
S2H	0.45	0.67	0.90	0.65	1.80	0.65	3.60	0.65
S3	0.45	0.68	0.90	0.67	1.80	0.66	3.60	0.66
S4L	0.45	0.67	0.90	0.67	1.80	0.67	3.60	0.67
S4M	0.45	0.66	0.90	0.65	1.80	0.66	3.60	0.66
S4H	0.45	0.66	0.90	0.65	1.80	0.63	3.60	0.63
S5L*								
S5M*								
S5H*								
C1L	0.45	0.67	0.90	0.68	1.80	0.67	3.60	0.67
C1M	0.45	0.66	0.90	0.66	1.80	0.66	3.60	0.66
C1H	0.45	0.67	0.90	0.65	1.80	0.65	3.60	0.65
C2L	0.45	0.68	0.90	0.67	1.80	0.67	3.60	0.63
C2M	0.45	0.68	0.90	0.65	1.80	0.64	3.60	0.64
C2H	0.45	0.68	0.90	0.65	1.80	0.64	3.60	0.64
C3L*								
C3M*								
C3H*								
PC1	0.45	0.72	0.90	0.66	1.80	0.67	3.60	0.63
PC2L	0.45	0.68	0.90	0.67	1.80	0.66	3.60	0.66
PC2M	0.45	0.67	0.90	0.64	1.80	0.65	3.60	0.65
PC2H	0.45	0.66	0.90	0.64	1.80	0.63	3.60	0.63
RM1L	0.45	0.73	0.90	0.66	1.80	0.68	3.60	0.64
RM1M	0.45	0.69	0.90	0.65	1.80	0.64	3.60	0.64
RM2L	0.45	0.71	0.90	0.66	1.80	0.67	3.60	0.63
RM2M	0.45	0.70	0.90	0.65	1.80	0.64	3.60	0.64
RM2H	0.45	0.69	0.90	0.65	1.80	0.64	3.60	0.64
URML*								
URMM*								
MH	0.38	0.66	0.75	0.67	1.50	0.67	3.00	0.67

**Shaded boxes and building types with an asterisk (*) indicate types that are not permitted by current seismic codes.*

Table 6-13 Special Building Nonstructural Acceleration-Sensitive Fragility - Moderate-Code (Moderate Special-MS) Seismic Design Level

Building Type	Median Spectral Acceleration (g) and Logstandard Deviation (Beta)							
	Slight		Moderate		Extensive		Complete	
	Median	Beta	Median	Beta	Median	Beta	Median	Beta
W1	0.38	0.71	0.75	0.68	1.50	0.68	3.00	0.65
W2	0.38	0.67	0.75	0.68	1.50	0.68	3.00	0.68
S1L	0.38	0.67	0.75	0.67	1.50	0.68	3.00	0.68
S1M	0.38	0.67	0.75	0.67	1.50	0.67	3.00	0.67
S1H	0.38	0.67	0.75	0.66	1.50	0.66	3.00	0.66
S2L	0.38	0.66	0.75	0.66	1.50	0.68	3.00	0.68
S2M	0.38	0.65	0.75	0.65	1.50	0.64	3.00	0.64
S2H	0.38	0.65	0.75	0.65	1.50	0.65	3.00	0.65
S3	0.38	0.66	0.75	0.66	1.50	0.66	3.00	0.66
S4L	0.38	0.67	0.75	0.66	1.50	0.65	3.00	0.65
S4M	0.38	0.65	0.75	0.65	1.50	0.65	3.00	0.65
S4H	0.38	0.65	0.75	0.65	1.50	0.65	3.00	0.65
S5L*								
S5M*								
S5H*								
C1L	0.38	0.68	0.75	0.66	1.50	0.68	3.00	0.68
C1M	0.38	0.66	0.75	0.65	1.50	0.65	3.00	0.65
C1H	0.38	0.65	0.75	0.65	1.50	0.65	3.00	0.65
C2L	0.38	0.67	0.75	0.67	1.50	0.67	3.00	0.67
C2M	0.38	0.65	0.75	0.64	1.50	0.66	3.00	0.66
C2H	0.38	0.65	0.75	0.64	1.50	0.64	3.00	0.64
C3L*								
C3M*								
C3H*								
PC1	0.38	0.67	0.75	0.67	1.50	0.65	3.00	0.65
PC2L	0.38	0.66	0.75	0.66	1.50	0.64	3.00	0.64
PC2M	0.38	0.64	0.75	0.64	1.50	0.64	3.00	0.64
PC2H	0.38	0.64	0.75	0.65	1.50	0.65	3.00	0.65
RM1L	0.38	0.67	0.75	0.67	1.50	0.67	3.00	0.67
RM1M	0.38	0.65	0.75	0.64	1.50	0.66	3.00	0.66
RM2L	0.38	0.67	0.75	0.67	1.50	0.67	3.00	0.67
RM2M	0.38	0.65	0.75	0.64	1.50	0.66	3.00	0.66
RM2H	0.38	0.65	0.75	0.64	1.50	0.64	3.00	0.64
URML*								
URMM*								
MH	0.38	0.66	0.75	0.67	1.50	0.67	3.00	0.67

**Shaded boxes and building types with an asterisk (*) indicate types that are not permitted by current seismic codes.*

Table 6-14 Special Building Nonstructural Acceleration-Sensitive Fragility - Low-Code (Low Special-LS) Seismic Design Level

Building Type	Median Spectral Acceleration (g) and Logstandard Deviation (Beta)							
	Slight		Moderate		Extensive		Complete	
	Median	Beta	Median	Beta	Median	Beta	Median	Beta
W1	0.30	0.71	0.60	0.68	1.20	0.66	2.40	0.65
W2	0.30	0.66	0.60	0.66	1.20	0.69	2.40	0.69
S1L	0.30	0.66	0.60	0.68	1.20	0.68	2.40	0.68
S1M	0.30	0.66	0.60	0.68	1.20	0.68	2.40	0.68
S1H	0.30	0.67	0.60	0.67	1.20	0.67	2.40	0.67
S2L	0.30	0.65	0.60	0.68	1.20	0.68	2.40	0.68
S2M	0.30	0.65	0.60	0.67	1.20	0.67	2.40	0.67
S2H	0.30	0.64	0.60	0.67	1.20	0.67	2.40	0.67
S3	0.30	0.65	0.60	0.67	1.20	0.67	2.40	0.67
S4L	0.30	0.65	0.60	0.68	1.20	0.68	2.40	0.68
S4M	0.30	0.64	0.60	0.68	1.20	0.68	2.40	0.68
S4H	0.30	0.64	0.60	0.67	1.20	0.67	2.40	0.67
S5L	0.30	0.65	0.60	0.68	1.20	0.68	2.40	0.68
S5M	0.30	0.64	0.60	0.67	1.20	0.67	2.40	0.67
S5H	0.30	0.64	0.60	0.67	1.20	0.67	2.40	0.67
C1L	0.30	0.65	0.60	0.68	1.20	0.68	2.40	0.68
C1M	0.30	0.64	0.60	0.67	1.20	0.67	2.40	0.67
C1H	0.30	0.67	0.60	0.67	1.20	0.67	2.40	0.67
C2L	0.30	0.66	0.60	0.66	1.20	0.65	2.40	0.65
C2M	0.30	0.63	0.60	0.65	1.20	0.65	2.40	0.65
C2H	0.30	0.63	0.60	0.66	1.20	0.66	2.40	0.66
C3L	0.30	0.65	0.60	0.67	1.20	0.67	2.40	0.67
C3M	0.30	0.63	0.60	0.66	1.20	0.66	2.40	0.66
C3H	0.30	0.63	0.60	0.67	1.20	0.67	2.40	0.67
PC1	0.30	0.66	0.60	0.65	1.20	0.65	2.40	0.65
PC2L	0.30	0.65	0.60	0.68	1.20	0.68	2.40	0.68
PC2M	0.30	0.63	0.60	0.67	1.20	0.67	2.40	0.67
PC2H	0.30	0.64	0.60	0.66	1.20	0.66	2.40	0.66
RM1L	0.30	0.66	0.60	0.66	1.20	0.65	2.40	0.65
RM1M	0.30	0.64	0.60	0.65	1.20	0.65	2.40	0.65
RM2L	0.30	0.66	0.60	0.66	1.20	0.66	2.40	0.66
RM2M	0.30	0.64	0.60	0.65	1.20	0.65	2.40	0.65
RM2H	0.30	0.63	0.60	0.65	1.20	0.65	2.40	0.65
URML	0.30	0.68	0.60	0.66	1.20	0.64	2.40	0.64
URMM	0.30	0.64	0.60	0.65	1.20	0.65	2.40	0.65
MH	0.38	0.66	0.75	0.67	1.50	0.67	3.00	0.67

6.5.3 Structural Fragility Curves – Equivalent Peak Ground Acceleration

Structural damage fragility curves are expressed in terms of an equivalent value of PGA (rather than spectral displacement) for evaluation of Special buildings that are components of utility and transportation systems. Only structural damage functions are developed based on PGA, since structural damage is considered the most appropriate measure of damage of utility and transportation system facilities. Similar methods could be used to develop nonstructural damage functions based on PGA. In this case, capacity curves are not necessary to estimate building response and PGA is used directly as the PEH input to building fragility curves.

This section provides equivalent-PGA fragility curves for Special buildings based on the structural damage functions of Table 6-6, Table 6-7 and Table 6-8 standard spectrum shape properties. These functions have the same format and are based on the same approach and assumptions as those described in Section 5.4.3 for the development of equivalent-PGA fragility curves for Code buildings. Currently, the Hazus transportation and utility system facilities are not classified into the Hazus specific building types as presented in these tables. As a result, the PGA-based fragilities presented in this section are not currently used in Hazus, however, they are presented as guidance and for potential use if a user has transportation and utility system facility inventories classified into Hazus specific building types.

The values given in Table 6-15, Table 6-16, and Table 6-17 are appropriate for use in the evaluation of scenario earthquakes whose demand spectrum shape is based on, or similar to, large magnitude, WUS ground shaking at soil sites (reference spectrum shape). For evaluation of building damage due to scenario earthquakes whose spectra are not similar to the reference spectrum shape, damage state median parameters may be adjusted to better represent equivalent-PGA structural fragility for the spectrum shape of interest.

Median values of equivalent PGA are adjusted for: (1) the site condition (if different from Site Class D) and (2) the ratio of long period spectral response (i.e., S_{A1}) to PGA (if different from a value of 1.5, the ratio of S_{A1} to PGA of the reference spectrum shape). Damage state variability is not adjusted assuming that the variability associated with ground shaking (although different for different source/site conditions) when combined with the uncertainty in damage state threshold, is approximately the same for all demand spectrum shapes.

Equivalent-PGA medians, given in Table 6-15, Table 6-16, and Table 6-17 for the reference spectrum shape, are adjusted to represent other spectrum shapes using the spectrum shape ratios of Table 5-26 and Table 5-27, the soil amplification factor, F_V, and Equation 5-6. In general, implementation of Equation 5-6 requires information on earthquake magnitude and source-to-site distance to estimate the spectrum shape ratio for rock sites, and 1-second period spectral acceleration at the site (to estimate the soil amplification factor).

Table 6-15 Equivalent-PGA Structural Fragility – Special High-Code (High Special-HS) Seismic Design Level

Building Type	Median Equivalent-PGA (g) and Logstandard Deviation (Beta)							
	Slight		Moderate		Extensive		Complete	
	Median	Beta	Median	Beta	Median	Beta	Median	Beta
W1	0.32	0.64	0.78	0.64	2.00	0.64	3.22	0.64
W2	0.35	0.64	0.82	0.64	1.76	0.64	3.13	0.64
S1L	0.25	0.64	0.44	0.64	0.92	0.64	2.17	0.64
S1M	0.17	0.64	0.34	0.64	0.85	0.64	2.10	0.64
S1H	0.13	0.64	0.26	0.64	0.65	0.64	1.73	0.64
S2L	0.33	0.64	0.58	0.64	1.10	0.64	2.07	0.64
S2M	0.18	0.64	0.35	0.64	0.97	0.64	2.34	0.64
S2H	0.14	0.64	0.27	0.64	0.81	0.64	2.13	0.64
S3	0.19	0.64	0.36	0.64	0.79	0.64	1.44	0.64
S4L	0.34	0.64	0.54	0.64	1.04	0.64	1.91	0.64
S4M	0.21	0.64	0.37	0.64	0.98	0.64	2.27	0.64
S4H	0.16	0.64	0.32	0.64	0.90	0.64	2.29	0.64
S5L*								
S5M*								
S5H*								
C1L	0.29	0.64	0.51	0.64	1.07	0.64	2.06	0.64
C1M	0.19	0.64	0.36	0.64	1.02	0.64	2.48	0.64
C1H	0.14	0.64	0.28	0.64	0.83	0.64	2.03	0.64
C2L	0.33	0.64	0.66	0.64	1.42	0.64	2.40	0.64
C2M	0.22	0.64	0.49	0.64	1.24	0.64	2.97	0.64
C2H	0.15	0.64	0.37	0.64	1.11	0.64	2.80	0.64
C3L*								
C3M*								
C3H*								
PC1	0.25	0.64	0.48	0.64	1.02	0.64	1.86	0.64
PC2L	0.32	0.64	0.51	0.64	1.03	0.64	1.78	0.64
PC2M	0.22	0.64	0.40	0.64	0.92	0.64	2.25	0.64
PC2H	0.15	0.64	0.30	0.64	0.83	0.64	2.13	0.64
RM1L	0.39	0.64	0.65	0.64	1.52	0.64	2.53	0.64
RM1M	0.25	0.64	0.50	0.64	1.15	0.64	2.76	0.64
RM2L	0.34	0.64	0.59	0.64	1.41	0.64	2.36	0.64
RM2M	0.22	0.64	0.43	0.64	1.05	0.64	2.65	0.64
RM2H	0.15	0.64	0.30	0.64	0.89	0.64	2.58	0.64
URML*								
URMM*								
MH	0.16	0.64	0.26	0.64	0.45	0.64	0.88	0.64

**Shaded boxes and building types with an asterisk (*) indicate types that are not permitted by current seismic codes.*

Table 6-16 Equivalent-PGA Structural Fragility – Special Moderate-Code (Moderate Special-MS) Seismic Design Level

Building Type	Median Equivalent-PGA (g) and Logstandard Deviation (Beta)							
	Slight		Moderate		Extensive		Complete	
	Median	Beta	Median	Beta	Median	Beta	Median	Beta
W1	0.32	0.64	0.59	0.64	1.32	0.64	2.08	0.64
W2	0.28	0.64	0.51	0.64	1.00	0.64	1.83	0.64
S1L	0.20	0.64	0.31	0.64	0.60	0.64	1.29	0.64
S1M	0.16	0.64	0.28	0.64	0.60	0.64	1.27	0.64
S1H	0.13	0.64	0.22	0.64	0.51	0.64	1.17	0.64
S2L	0.27	0.64	0.37	0.64	0.67	0.64	1.27	0.64
S2M	0.17	0.64	0.28	0.64	0.69	0.64	1.40	0.64
S2H	0.14	0.64	0.23	0.64	0.63	0.64	1.44	0.64
S3	0.18	0.64	0.26	0.64	0.46	0.64	0.86	0.64
S4L	0.26	0.64	0.36	0.64	0.61	0.64	1.17	0.64
S4M	0.18	0.64	0.29	0.64	0.69	0.64	1.33	0.64
S4H	0.16	0.64	0.26	0.64	0.66	0.64	1.42	0.64
S5L*								
S5M*								
S5H*								
C1L	0.23	0.64	0.33	0.64	0.63	0.64	1.22	0.64
C1M	0.17	0.64	0.28	0.64	0.70	0.64	1.38	0.64
C1H	0.14	0.64	0.23	0.64	0.59	0.64	1.15	0.64
C2L	0.26	0.64	0.44	0.64	0.77	0.64	1.34	0.64
C2M	0.20	0.64	0.35	0.64	0.81	0.64	1.63	0.64
C2H	0.15	0.64	0.30	0.64	0.78	0.64	1.63	0.64
C3L*								
C3M*								
C3H*								
PC1	0.24	0.64	0.33	0.64	0.63	0.64	1.05	0.64
PC2L	0.24	0.64	0.35	0.64	0.59	0.64	1.06	0.64
PC2M	0.19	0.64	0.29	0.64	0.62	0.64	1.27	0.64
PC2H	0.15	0.64	0.25	0.64	0.60	0.64	1.30	0.64
RM1L	0.31	0.64	0.44	0.64	0.79	0.64	1.33	0.64
RM1M	0.24	0.64	0.36	0.64	0.74	0.64	1.65	0.64
RM2L	0.28	0.64	0.41	0.64	0.74	0.64	1.27	0.64
RM2M	0.21	0.64	0.32	0.64	0.69	0.64	1.58	0.64
RM2H	0.15	0.64	0.25	0.64	0.64	0.64	1.53	0.64
URML*								
URMM*								
MH	0.16	0.64	0.26	0.64	0.45	0.64	0.88	0.64

**Shaded boxes and building types with an asterisk (*) indicate types that are not permitted by current seismic codes.*

Table 6-17 Equivalent-PGA Structural Fragility – Special Low-Code (Low Special-LS) Seismic Design Level

Building Type	Median Equivalent-PGA (g) and Logstandard Deviation (Beta)							
	Slight		Moderate		Extensive		Complete	
	Median	Beta	Median	Beta	Median	Beta	Median	Beta
W1	0.28	0.64	0.50	0.64	1.00	0.64	1.51	0.64
W2	0.21	0.64	0.34	0.64	0.68	0.64	1.10	0.64
S1L	0.16	0.64	0.23	0.64	0.42	0.64	0.71	0.64
S1M	0.15	0.64	0.23	0.64	0.42	0.64	0.73	0.64
S1H	0.13	0.64	0.20	0.64	0.40	0.64	0.71	0.64
S2L	0.19	0.64	0.25	0.64	0.44	0.64	0.74	0.64
S2M	0.16	0.64	0.24	0.64	0.52	0.64	0.88	0.64
S2H	0.14	0.64	0.21	0.64	0.50	0.64	0.93	0.64
S3	0.14	0.64	0.18	0.64	0.30	0.64	0.57	0.64
S4L	0.19	0.64	0.23	0.64	0.38	0.64	0.68	0.64
S4M	0.16	0.64	0.23	0.64	0.47	0.64	0.81	0.64
S4H	0.15	0.64	0.23	0.64	0.48	0.64	0.87	0.64
S5L	0.18	0.64	0.26	0.64	0.41	0.64	0.68	0.64
S5M	0.14	0.64	0.24	0.64	0.50	0.64	0.80	0.64
S5H	0.13	0.64	0.24	0.64	0.51	0.64	0.84	0.64
C1L	0.17	0.64	0.22	0.64	0.39	0.64	0.67	0.64
C1M	0.15	0.64	0.23	0.64	0.48	0.64	0.80	0.64
C1H	0.13	0.64	0.20	0.64	0.39	0.64	0.66	0.64
C2L	0.19	0.64	0.27	0.64	0.44	0.64	0.79	0.64
C2M	0.16	0.64	0.26	0.64	0.56	0.64	0.93	0.64
C2H	0.14	0.64	0.25	0.64	0.56	0.64	0.96	0.64
C3L	0.17	0.64	0.25	0.64	0.39	0.64	0.65	0.64
C3M	0.14	0.64	0.23	0.64	0.46	0.64	0.75	0.64
C3H	0.12	0.64	0.22	0.64	0.48	0.64	0.79	0.64
PC1	0.18	0.64	0.24	0.64	0.38	0.64	0.65	0.64
PC2L	0.18	0.64	0.23	0.64	0.36	0.64	0.66	0.64
PC2M	0.16	0.64	0.22	0.64	0.45	0.64	0.79	0.64
PC2H	0.14	0.64	0.21	0.64	0.45	0.64	0.81	0.64
RM1L	0.22	0.64	0.29	0.64	0.44	0.64	0.80	0.64
RM1M	0.19	0.64	0.26	0.64	0.50	0.64	0.92	0.64
RM2L	0.20	0.64	0.27	0.64	0.41	0.64	0.77	0.64
RM2M	0.17	0.64	0.24	0.64	0.47	0.64	0.88	0.64
RM2H	0.14	0.64	0.22	0.64	0.49	0.64	0.92	0.64
URML	0.19	0.64	0.28	0.64	0.47	0.64	0.68	0.64
URMM	0.14	0.64	0.22	0.64	0.38	0.64	0.70	0.64
MH	0.16	0.64	0.26	0.64	0.45	0.64	0.88	0.64

6.6 Damage Due to Ground Failure – Special Buildings

Damage to Special buildings due to ground failure is assumed to be the same as the damage to Code buildings for the same amount of permanent ground deformation (PGD). Fragility curves developed in Section 5.5 for Code buildings are also appropriate for prediction of damage to Special buildings due to ground failure.

6.7 Evaluation of Building Damage – Essential Facilities

6.7.1 Overview

Special building capacity and fragility curves for structural and nonstructural systems are used to predict essential facility damage when the user is able to determine that the essential facility is superior to a typical building of the specific building type and design level of interest. If such a determination cannot be made by the user, then the Code building functions of Section 5 are used to evaluate essential building damage. These criteria are summarized in Table 6-18.

Table 6-18 Criteria for Evaluating Essential Facility Damage

Evaluate Essential Facility Using:	User Deems Essential Facility to be:
Code building damage functions (High-Code, Moderate-Code, Low-Code, and Pre-Code functions)	Typical of the specific building type and seismic design level of interest (i.e., no special seismic protection of components)
Special building damage functions (Special High-Code, Special Moderate-Code, and Special Low-Code functions)	Superior to the specific building type and seismic design level of interest (e.g., 50% stronger lateral force-resisting structural system, and special anchorage and bracing of nonstructural components)

During an earthquake, the essential facilities may be damaged either by ground shaking, ground failure, or both. Essential facilities are evaluated separately for the two modes, ground shaking and ground failure, and the resulting damage state probabilities combined for evaluation of loss.

6.7.2 Damage Due to Ground Shaking

Damage to essential facilities due to ground shaking uses the same methods as those described in Section 5.6.1 for Code buildings, with the exception that Special buildings are assumed to have less degradation and greater effective damping than Code buildings.

6.7.2.1 Demand Spectrum Reduction for Effective Damping – Special Buildings

Demand spectra for evaluation of damage to Special buildings are constructed using the same approach, assumptions, and formulas as those described in Section 5.6.1.1 for Code buildings, except values of the degradation factor, k , that defines the effective amount of hysteretic damping as a function of duration are different for Special buildings. Degradation factors for Special buildings are given in Table 6-19.

Figure 6-5 shows typical demand spectra (spectral acceleration plotted as a function of spectral displacement) for three demand levels, estimated for **M**=7.0 at 20 km, for the WUS, on Site Class E. These three demand levels represent Short (k = 0.90), Moderate (k = 0.60), and Long (k = 0.40) duration ground shaking, respectively. Also shown in the figure is the building capacity curve of a low-rise Special building (Special Moderate-Code seismic design) that was used to estimate effective damping. The intersection of the capacity curve with each of the three demand spectra illustrates the significance of duration (damping) on building response.

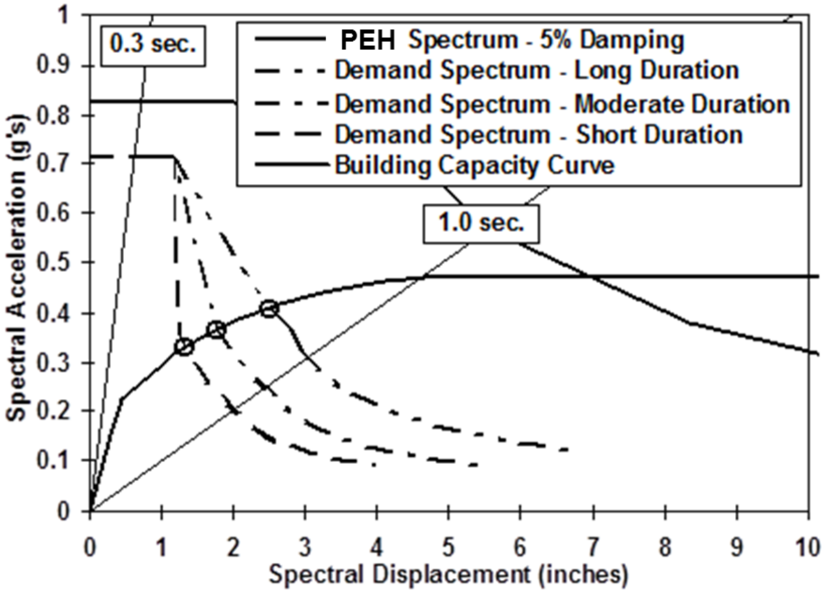


Figure 6-5 Example Demand Spectra – Special Building

Comparison of Figure 6-5 with Figure 5-7 (same example building and PEH demand, except capacity curve and damping represents Code building properties) illustrates the significance of increased strength and damping (reduced degradation) of Special buildings on the reduction of building displacement. In this case, the Special building displaces only about one half as much as a comparable Code building for the same level of PEH demand. Forces on nonstructural acceleration-sensitive components are not reduced, but are slightly increased, due to the higher strength of the Special building.

Table 6-19 Special Building Degradation Factor (k) as a Function of Short, Moderate, and Long Earthquake Duration

Building Type		Special High-Code Design			Special Moderate-Code Design			Special Low-Code Design		
No.	Label	Short	Moderate	Long	Short	Moderate	Long	Short	Moderate	Long
1	W1	1.0	1.0	0.7	1.0	0.8	0.5	0.9	0.6	0.3
2	W2	1.0	0.8	0.6	0.9	0.6	0.4	0.8	0.4	0.2
3	S1L	1.0	0.8	0.6	0.9	0.6	0.4	0.8	0.4	0.2
4	S1M	1.0	0.8	0.6	0.9	0.6	0.4	0.8	0.4	0.2
5	S1H	1.0	0.8	0.6	0.9	0.6	0.4	0.8	0.4	0.2
6	S2L	0.8	0.6	0.4	0.7	0.5	0.3	0.6	0.4	0.2
7	S2M	0.8	0.6	0.4	0.7	0.5	0.3	0.6	0.4	0.2
8	S2H	0.8	0.6	0.4	0.7	0.5	0.3	0.6	0.4	0.2
9	S3	0.8	0.6	0.4	0.7	0.5	0.3	0.6	0.4	0.2
10	S4L	0.8	0.6	0.4	0.7	0.5	0.3	0.6	0.4	0.2
11	S4M	0.8	0.6	0.4	0.7	0.5	0.3	0.6	0.4	0.2
12	S4H	0.8	0.6	0.4	0.7	0.5	0.3	0.6	0.4	0.2
13	S5L	0.6	0.4	0.2	0.6	0.4	0.2	0.6	0.4	0.2
14	S5M	0.6	0.4	0.2	0.6	0.4	0.2	0.6	0.4	0.2
15	S5H	0.6	0.4	0.2	0.6	0.4	0.2	0.6	0.4	0.2
16	C1L	1.0	0.8	0.6	0.9	0.6	0.4	0.8	0.4	0.2
17	C1M	1.0	0.8	0.6	0.9	0.6	0.4	0.8	0.4	0.2
18	C1H	1.0	0.8	0.6	0.9	0.6	0.4	0.8	0.4	0.2
19	C2L	1.0	0.8	0.6	0.9	0.6	0.4	0.8	0.4	0.2
20	C2M	1.0	0.8	0.6	0.9	0.6	0.4	0.8	0.4	0.2
21	C2H	1.0	0.8	0.6	0.9	0.6	0.4	0.8	0.4	0.2
22	C3L	0.6	0.4	0.2	0.6	0.4	0.2	0.6	0.4	0.2
23	C3M	0.6	0.4	0.2	0.6	0.4	0.2	0.6	0.4	0.2
24	C3H	0.6	0.4	0.2	0.6	0.4	0.2	0.6	0.4	0.2
25	PC1	0.8	0.6	0.4	0.7	0.5	0.3	0.6	0.4	0.2
26	PC2L	0.8	0.6	0.4	0.7	0.5	0.3	0.6	0.4	0.2
27	PC2	0.8	0.6	0.4	0.7	0.5	0.3	0.6	0.4	0.2
28	PC2H	0.8	0.6	0.4	0.7	0.5	0.3	0.6	0.4	0.2
29	RM1L	1.0	0.8	0.6	0.9	0.6	0.4	0.8	0.4	0.2
30	RM1	1.0	0.8	0.6	0.9	0.6	0.4	0.8	0.4	0.2
31	RM2L	1.0	0.8	0.6	0.9	0.6	0.4	0.8	0.4	0.2
32	RM2	1.0	0.8	0.6	0.9	0.6	0.4	0.8	0.4	0.2
33	RM2	1.0	0.8	0.6	0.9	0.6	0.4	0.8	0.4	0.2
34	URM	0.6	0.4	0.2	0.6	0.4	0.2	0.6	0.4	0.2
35	URM	0.6	0.4	0.2	0.6	0.4	0.2	0.6	0.4	0.2
36	MH	0.9	0.6	0.4	0.9	0.6	0.4	0.9	0.6	0.4

6.7.2.2 Damage State Probability

Structural and nonstructural fragility curves of essential facilities are evaluated for spectral displacement and spectral acceleration defined by the intersection of the capacity and demand curves. Each of these curves describe the cumulative probability of being in, or exceeding, a particular damage state. Nonstructural components (both drift- and acceleration-sensitive components) may, in some cases, be dependent on the structural damage state (e.g., Complete structural damage may cause complete nonstructural damage). The methodology assumes nonstructural damage states to be independent of structural damage states. Cumulative probabilities are differenced to obtain discrete probabilities of being in each of the five damage states.

6.7.3 Combined Damage Due to Ground Failure and Ground Shaking

Damage to essential facilities is based either on Code building damage functions or Special building damage functions. Code building damage due to ground shaking is combined with damage due to ground failure as specified in Section 5.6.2. Special building damage due to ground failure (Section 6.6) is combined with damage due to ground shaking (Section 6.5) using the same approach, assumptions, and formulas as those given for Code buildings.

6.8 Restoration Curves

Component restoration curves are provided for each damage state to evaluate loss of function. Restoration curves describe the fraction or percentage of the component that is expected to be open or operational as a function of time following the earthquake. For example, an extensively damaged facility might be closed (0% functional) immediately following the earthquake, but 100% functional after 30 days. Restoration curves are based on generic ATC-13 data (Applied Technology Council, 1985) for the social function classifications of interest and are approximated as normal curves characterized by a mean and a standard deviation in days for each damage state. The parameters of these restoration curves are given in Table 6-20 and are fully user-editable.

Hazus functionality estimates are based solely on physical damage to the building/facility, and do not take emergency response or contingency plans into consideration (e.g., hospitals which could operate their emergency room from the parking lot). Functionality estimates also do not consider direct utility outage or potential cascading effects. While no precise definition of functionality has been developed for the Hazus restoration functions, one interpretation of the Hazus functionality results is as follows:

A “functional” building/facility may be used for its intended purpose, while a “non-functional” building/facility can no longer be used for its intended purpose. The Hazus functionality estimates, which range from 0 – 100 %, may be interpreted as:

- 0-25% functionality – building/facility is likely to be non-functional
- 25-75% functionality – building/facility is likely to allow limited operations (e.g., selected parts of the building/facility may be used)
- 75-100% functionality – building/facility is likely to be functional

Table 6-20 Generic Restoration Functions for Essential Facilities (Days

EF	Description	Slight		Moderate		Extensive		Complete	
		Mean	Sigma	Mean	Sigma	Mean	Sigma	Mean	Sigma
EDFLT	Default for Emergency Response Facility	5	1	20	2	90	10	180	20
EFEO	Emergency Operation Centers	5	1	20	2	90	10	180	20
EFFS	Fire Station	5	1	20	2	90	10	180	20
EFHL	Large Hospital (greater than 150 beds)	5	1	20	2	90	10	180	20
EFHM	Medium Hospital (50 to 150 Beds)	5	1	20	2	90	10	180	20
EFHS	Small Hospital (less than 50 Beds)	5	1	20	2	90	10	180	20
EFMC	Medical Clinics and Labs	5	1	20	2	90	10	180	20
EFPS	Police Station	5	1	20	2	90	10	180	20
EFS1	Grade Schools (Primary and High Schools)	5	1	20	2	90	10	180	20
EFS2	Colleges/ Universities	5	1	20	2	90	10	180	20
FDFLT	Default for Fire Station	5	1	20	2	90	10	180	20
MDFLT	Default for Medical	5	1	20	2	90	10	180	20
PDFLT	Default for Police	5	1	20	2	90	10	180	20
SDFLT	Default for School	5	1	20	2	90	10	180	20

6.9 Guidance for Expert Users

This section provides guidance for users who are seismic/structural experts interested in modifying essential facility damage functions supplied with the methodology. This section also provides the expert user with guidance regarding the selection of the appropriate mix of design levels for the region of interest, and describes the estimation of damage to High Potential Loss (HPL) facilities.

6.9.1 Selection of Representative Seismic Design Level

The methodology permits the user to select the seismic design level considered appropriate for each essential facility and to designate the facility as a Special building, when designed and constructed to above-Code standards. In general, performance of essential facilities is not expected to be better than the typical (Code) building of the representative specific building type. Exceptions to this generalization include California hospitals of recent (post-1973) construction. If the user is not able to determine that the essential facility is significantly better than average, then the facility should be modeled using Code building damage functions (i.e., the same methods as those developed in Section 5 for the general building stock).

Table 6-21 provides guidance for selecting appropriate building damage functions for essential facilities based on design vintage. These guidelines are applicable to the following facilities:

- Hospitals and other medical facilities having surgery or emergency treatment areas (i.e., acute care facilities),
- Fire and police stations, and
- Municipal government disaster operation and communication centers deemed (for design) to be vital in emergencies, provided that seismic codes (e.g., *Uniform Building Code*) were adopted and enforced in the study area of interest. Such adoption and enforcement is generally true for jurisdictions of California, but may not be true for other areas.

Table 6-21 Guidelines for Selection of Damage Functions for Essential Facilities Based on UBC Seismic Zone and Building Age for California

UBC **Seismic Zone (NEHRP Map Area)**	**Post-1973**	**1941 – 1973**	**Pre-1941**
Zone 4 (Map Area 7)	Special High-Code	Moderate-Code	Pre-Code (W1 = Moderate-Code)
Zone 3 (Map Area 6)	Special Moderate-Code	Moderate-Code	Pre-Code (W1 = Moderate-Code)
Zone 2B (Map Area 5)	Moderate-Code	Low-Code	Pre-Code (W1 = Low-Code)
Zone 2A (Map Area 4)	Low-Code	Low-Code	Pre-Code (W1 = Low-Code)
Zone 1 Map Area 2/3)	Low-Code	Pre-Code (W1 = Low-Code)	Pre-Code (W1 = Low-Code)
Zone 0 (Map Area 1)	Pre-Code (W1 = Low-Code)	Pre-Code (W1 = Low-Code)	Pre-Code (W1 = Low-Code)

The guidelines given in Table 6-21 assume that essential buildings in the Study Region are not designed for wind. The user should consider the possibility that mid-rise and high-rise facilities could be designed for wind and may have considerable lateral strength, even if not designed for earthquake. Users must be knowledgeable about the type and history of construction in the Study Region of interest and apply engineering judgment in assigning essential facilities to a building type and seismic design level.

6.9.2 High Potential Loss (HPL) Facilities

This section describes damage evaluation of HPL facilities. HPL facilities are likely to cause heavy earthquake losses, if significantly damaged. Examples of such facilities include nuclear power plants, certain military and industrial facilities, dams, etc. Currently, only military facilities are modeled for potential losses, while other HPL facilities are assessed for exposure to PEH hazards.

6.9.2.1 Input Requirements and Output Information

The importance of these facilities (in terms of potential earthquake losses) suggests that a damage assessment should be done in a special way compared to ordinary buildings. Each HPL facility should be treated on an individual basis by users who have sufficient expertise to evaluate damage to such facilities. Required input to the damage evaluation module includes the following items:

- Capacity curves that represent median (typical) properties of the HPL facility structure, or a related set of engineering parameters, such as period, yield strength, and ultimate capacity, that may be used by seismic/structural engineering experts with the methods of Section 5 to select representative damage functions.
- Fragility curves for the HPL facility under consideration, or a related set of engineering parameters that can be used by seismic/structural engineering experts with the methods of Section 5 to select appropriate damage functions.

The direct output (damage estimate) from implementation of the fragility curves is an estimate of the probability of being in, or exceeding, each damage state for the given level of ground shaking. This output is used directly as an input to other damage or loss estimation methods or combined with inventory information to predict the distribution of damage as a function of facility type, and geographical location. In the latter case, the number and geographical location of facilities of interest would be a required input to the damage estimation method.

6.9.2.2 Form of Damage Functions and Damage Evaluation

The form of user-supplied HPL facility damage functions should be the same as that of buildings (Section 5) and their use in the methodology would be similar to that of essential facilities.

Section 7. Direct Physical Damage to Transportation Systems

This section describes the methodology for estimating direct physical damage to Transportation Systems, which include the following seven systems:

- Highway
- Railway
- Light Rail
- Bus
- Port
- Ferry
- Airport

7.1 Highway Transportation System

This section presents an earthquake loss estimation methodology for highway transportation systems, consisting of roadways, bridges, and tunnels. Roads located on soft soil or fill, or roads which cross a surface fault rupture can experience failure resulting in loss of functionality. Bridges that fail usually cause significant disruptions to the transportation network, especially bridges that cross waterways. Likewise, tunnels are often not redundant, and when a tunnel becomes non-functional it is likely to cause a major disruption to transportation systems. Past earthquake damage reveals that bridges and tunnels are vulnerable to both ground shaking and ground failure, while roads are significantly affected by ground failure alone.

The scope of this section includes development of methods for estimation of earthquake damage to a highway transportation system given knowledge of the system's components (i.e., roadways, bridges, or tunnels), the classification of each component (e.g., for roadways, whether the road is a major road or urban road), and the hazards (i.e., peak ground acceleration and/or permanent ground deformation). Damage states describing the level of damage to each highway system component are defined (i.e., None, Slight, Moderate, Extensive, or Complete). Damage states are related to a damage ratio, defined as the ratio of repair to replacement cost for evaluation of direct economic loss.

Fragility curves are developed for each type of highway system component. These curves describe the probability of reaching or exceeding each damage state given the level of ground motion or ground deformation and are based on the classification of each facility. Beginning with the November 2019 Hazus data release, many of the transportation system layers, including the National Bridge Inventory, are directly updated from the Homeland Infrastructure Foundation-Level Data (HIFLD) Open datasets. Details on how the initial baseline classifications and inventory parameters are assigned to transportation systems are provided in the *Hazus Inventory Technical Manual*.

Component restoration curves are provided for each damage state to evaluate loss of function. Restoration curves describe the fraction, or percentage, of the component that is expected to be open or operational as a function of time following the earthquake. For example, an extensively damaged roadway link might be closed (0% functional) immediately following the earthquake, but 100% functional after 30 days.

Hazus functionality estimates are based solely on physical damage to the building/facility, and do not take emergency response or contingency plans into consideration (e.g., hospitals which could operate their emergency room from the parking lot). Functionality estimates also do not consider direct utility outage or potential cascading effects. While no precise definition of functionality has been developed for the Hazus restoration functions, one interpretation of the Hazus functionality results is as follows:

A “functional” building/facility may be used for its intended purpose, while a “non-functional” building/facility can no longer be used for its intended purpose. The Hazus functionality estimates, which range from 0 – 100%, may be interpreted as:

- 0-25% functionality – building/facility is likely to be non-functional
- 25-75% functionality – building/facility is likely to allow limited operations (e.g., selected parts of the building/facility may be used)
- 75-100% functionality – building/facility is likely to be functional

7.1.1 Input Requirements and Output Information

Descriptions of required input to estimate damage to each highway system component are given below.

- Roadways:
  - Roadway classification
  - Geographical location of roadway links (polyline segments)
  - Permanent ground deformation (PGD) at roadway link
- Bridges:
  - Bridge classification
  - Geographical location of bridge (longitude and latitude)
  - Peak ground acceleration (PGA), spectral accelerations at 0.3 sec and 1.0 sec, and PGD at bridge
- Tunnels:
  - Tunnel classification
  - Geographical location of tunnels (longitude and latitude)
  - PGA and PGD at tunnel

Direct damage output for highway systems includes probability estimates of (1) component functionality, as described above and (2) physical damage expressed in terms of the component’s damage ratio. Note that damage ratios, which are input to direct economic loss methods, are described in Section 11.

Component functionality is described by the damage state probability (immediately following the earthquake) and by the associated fraction or percentage of the component that is expected to be functional after a specified period of time.

Interdependence of components on overall system functionality is not addressed by the methodology. Such considerations require a network system analysis that would be performed separately by a highway system expert.

7.1.2 Form of Damage Functions

Damage functions or fragility curves for all three highway system components mentioned above are modeled as lognormally distributed functions that give the probability of reaching or exceeding different damage states for a given level of ground motion or ground failure. Each fragility curve is characterized by a median value of ground motion or ground failure and an associated dispersion factor (lognormal standard deviation). Ground motion is quantified in terms of peak ground acceleration (PGA) and spectral acceleration (Sa), and ground failure is quantified in terms of permanent ground displacement (PGD).

- For roadways, fragility curves are defined in terms of PGD.
- For bridges, fragility curves are defined in terms of Sa (at 0.3 seconds), Sa (at 1.0 second), and PGD.
- For tunnels, fragility curves are defined in terms of PGA and PGD.

Definitions of various damage states and the methodology used in deriving the fragility curves are presented in the following sections.

7.1.3 Description of Highway Components

As mentioned previously, a highway system is composed of three components: roadways, bridges, and tunnels. In this section, a brief description of each is given.

Roadways: Roadways are classified as major roads or urban roads. Major roads include interstate and state highways and other roads with four lanes or more. Parkways are also classified as major roads. Urban roads include intercity roads and other roads with two lanes.

Bridges: Bridges are classified based on the following structural characteristics:

- Seismic Design
- Number of spans: single vs. multiple span bridges
- Structure type: concrete, steel, and others
- Pier type: multiple column bents, single column bents, and pier walls
- Abutment type and bearing type: monolithic vs. non-monolithic, high rocker bearings, low steel bearings, and neoprene rubber bearings
- Span continuity: continuous, discontinuous (in-span hinges), and simply supported

The seismic design of a bridge is taken into account in terms of the (*i*) spectrum modification factor, (*ii*) strength reduction factor due to cyclic motion, (*iii*) drift limits, and (*iv*) the longitudinal reinforcement ratio.

This classification scheme incorporates various parameters that affect damage into fragility analysis and provides a means to obtain better fragility curves when data become available. A total of 28 classes (HWB1 through HWB28) have been defined this way, as listed in Table 7-1. These classes differentiate between the different bridge characteristics found in the National Bridge Inventory (NBI). For example, year built from the NBI is used to classify as seismic if built in 1990 or later in California, and 1975 or later outside of California. Further details are provided in the *Hazus Inventory Technical Manual*.

Table 7-1 Hazus Bridge Classification Scheme

Class	NBI Class	State	Year Built	# Spans	Length of Max. Span (meter)	Length less than 20 m	K_{3D}	I-shape	Design	Description
HWB1	All	Non-CA	<1990		> 150	N/A	EQ1	0	Conventional	Major Bridge – Length >150 m
HWB1	All	CA	<1975		> 150	N/A	EQ1	0	Conventional	Major Bridge – Length >150 m
HWB2	All	Non-CA	>=1990		> 150	N/A	EQ1	0	Seismic	Major Bridge – Length > 150 m
HWB2	All	CA	>=1975		> 150	N/A	EQ1	0	Seismic	Major Bridge – Length >150 m
HWB3	All	Non-CA	<1990	1		N/A	EQ1	1	Conventional	Single Span
HWB3	All	CA	<1975	1		N/A	EQ1	1	Conventional	Single Span
HWB4	All	Non-CA	>=1990	1		N/A	EQ1	1	Seismic	Single Span
HWB4	All	CA	>=1975	1		N/A	EQ1	1	Seismic	Single Span
HWB5	101-106	Non-CA	<1990			N/A	EQ1	0	Conventional	Multi-Col. Bent, Simple Support – Concrete
HWB6	101-106	CA	<1975			N/A	EQ1	0	Conventional	Multi-Col. Bent, Simple Support – Concrete
HWB7	101-106	Non-CA	>=1990			N/A	EQ1	0	Seismic	Multi-Col. Bent, Simple Support – Concrete
HWB7	101-106	CA	>=1975			N/A	EQ1	0	Seismic	Multi-Col. Bent, Simple Support – Concrete
HWB8	205-206	CA	<1975			N/A	EQ2	0	Conventional	Single Col., Box Girder – Continuous Concrete
HWB9	205-206	CA	>=1975			N/A	EQ3	0	Seismic	Single Col., Box Girder – Continuous Concrete
HWB10	201-206	Non-CA	<1990			N/A	EQ2	1	Conventional	Continuous Concrete
HWB10	201-206	CA	<1975			N/A	EQ2	1	Conventional	Continuous Concrete
HWB11	201-206	Non-CA	>=1990			N/A	EQ3	1	Seismic	Continuous Concrete
HWB11	201-206	CA	>=1975			N/A	EQ3	1	Seismic	Continuous Concrete

Class	NBI Class	State	Year Built	# Spans	Length of Max. Span (meter)	Length less than 20 m	K_{3D}	I-shape	Design	Description
HWB12	301-306	Non-CA	<1990			No	EQ4	0	Conventional	Multi-Col. Bent, Simple Support – Steel
HWB13	301-306	CA	<1975			No	EQ4	0	Conventional	Multi-Col. Bent, Simple Support – Steel
HWB14	301-306	Non-CA	>=1990			N/A	EQ1	0	Seismic	Multi-Col. Bent, Simple Support – Steel
HWB14	301-306	CA	>=1975			N/A	EQ1	0	Seismic	Multi-Col. Bent, Simple Support – Steel
HWB15	402-410	Non-CA	<1990			No	EQ5	1	Conventional	Continuous Steel
HWB15	402-410	CA	<1975			No	EQ5	1	Conventional	Continuous Steel
HWB16	402-410	Non-CA	>=1990			N/A	EQ3	1	Seismic	Continuous Steel
HWB16	402-410	CA	>=1975			N/A	EQ3	1	Seismic	Continuous Steel
HWB17	501-506	Non-CA	<1990			N/A	EQ1	0	Conventional	Multi-Col. Bent, Simple Support – Prestressed Concrete
HWB18	501-506	CA	<1975			N/A	EQ1	0	Conventional	Multi-Col. Bent, Simple Support – Prestressed Concrete
HWB19	501-506	Non-CA	>=1990			N/A	EQ1	0	Seismic	Multi-Col. Bent, Simple Support – Prestressed Concrete
HWB19	501-506	CA	>=1975			N/A	EQ1	0	Seismic	Multi-Col. Bent, Simple Support – Prestressed Concrete
HWB20	605-606	CA	<1975			N/A	EQ2	0	Conventional	Single Col., Box Girder – Prestressed Continuous Concrete
HWB21	605-606	CA	>=1975			N/A	EQ3	0	Seismic	Single Col., Box Girder – Prestressed Continuous Concrete

Class	NBI Class	State	Year Built	# Spans	Length of Max. Span (meter)	Length less than 20 m	K_{3D}	I-shape	Design	Description
HWB22	601-607	Non-CA	<1990			N/A	EQ2	1	Conventional	Continuous Concrete
HWB22	601-607	CA	<1975			N/A	EQ2	1	Conventional	Continuous Concrete
HWB23	601-607	Non-CA	>=1990			N/A	EQ3	1	Seismic	Continuous Concrete
HWB23	601-607	CA	>=1975			N/A	EQ3	1	Seismic	Continuous Concrete
HWB24	301-306	Non-CA	<1990			Yes	EQ6	0	Conventional	Multi-Col. Bent, Simple Support – Steel
HWB25	301-306	CA	<1975			Yes	EQ6	0	Conventional	Multi-Col. Bent, Simple Support – Steel
HWB26	402-410	Non-CA	<1990			Yes	EQ7	1	Conventional	Continuous Steel
HWB27	402-410	CA	<1975			Yes	EQ7	1	Conventional	Continuous Steel
HWB28										All other bridges that are not classified

EQ1 through EQ7 in Table 7-1 are equations for evaluating K_{3D}. K_{3D} is a factor that modifies the piers' 2-dimensional capacity to allow for the 3-dimensional arch action in the deck. All of the equations have the same functional form; $K_{3D} = 1 + A / (N – B)$, where N is the number of spans and the parameters A and B are given in Table 7-2.

The Ishape term (given in Table 7-1) is a Boolean indicator. The Kshape factor is the modifier that converts cases for short periods to an equivalent spectral amplitude at T=1.0 second. When Ishape = 0, the Kshape factor does not apply. When Ishape = 1, the Kshape factor applies. Later in this section, the use of the Kshape factor will be illustrated through an example.

The 28 bridge classes in Table 7-1 (HWB1 through HWB28) reflect the maximum number of combinations for 'standard' bridge classes. Attributes such as the skewness and number of spans are accounted for in the evaluation of damage potential through a modification scheme that is presented later in this section.

Table 7-2 Coefficients for Evaluating K_{3D}

Equation	A	B	K_{3D}
EQ1	0.25	1	$1 + 0.25 / (N – 1)$
EQ2	0.33	0	$1 + 0.33 / (N)$
EQ3	0.33	1	$1 + 0.33 / (N – 1)$
EQ4	0.09	1	$1 + 0.09 / (N – 1)$

Equation	A	B	K_{3D}
EQ5	0.05	0	1 + 0.05 / (N)
EQ6	0.20	1	1 + 0.20 / (N – 1)
EQ7	0.10	0	1 + 0.10 / (N)

Tunnels: Tunnels are classified as bored/drilled or cut and cover.

7.1.4 Definitions of Damage States

A total of five damage states are defined for highway system components. These are None, Slight, Moderate, Extensive, and Complete.

Slight Damage

- For roadways, Slight damage is defined by slight settlement (a few inches) or offset of the ground.
- For bridges, Slight damage is defined by minor cracking and spalling to the abutment, cracks in shear keys at abutments, minor spalling and cracks at hinges, minor spalling at the column (damage requires no more than cosmetic repair), or minor cracking to the deck.
- For tunnels, Slight damage is defined by minor cracking of the tunnel liner (damage requires no more than cosmetic repair) and some rock falling, or by slight settlement of the ground at a tunnel portal.

Moderate Damage

- For roadways, Moderate damage is defined by moderate settlement (several inches) or offset of the ground.
- For bridges, Moderate damage is defined by any column experiencing moderate (shear cracks) cracking and spalling (column structurally still sound), moderate movement of the abutment (<2 inches), extensive cracking and spalling of shear keys, any connection having cracked shear keys or bent bolts, keeper bar failure without unseating, rocker bearing failure, or moderate settlement of the approach.
- For tunnels, Moderate damage is defined by moderate cracking of the tunnel liner and rock falling.

Extensive Damage

- For roadways, Extensive damage is defined by major settlement of the ground (a few feet).
- For bridges, Extensive damage is defined by any column degrading without collapse: shear failure – (column structurally unsafe), significant residual movement at connections, major settlement approach, vertical offset of the abutment, differential settlement at connections, or shear key failure at abutments.
- For tunnels, Extensive damage is characterized by major ground settlement at a tunnel portal and extensive cracking of the tunnel liner.

Complete Damage

- For roadways, Complete damage is defined by major settlement of the ground (i.e., same as Extensive damage).

- For bridges, Complete damage is defined by any column collapsing and connection losing all bearing support, which may lead to imminent deck collapse, or tilting of substructure due to foundation failure.
- For tunnels, Complete damage is characterized by major cracking of the tunnel liner, which may include possible collapse.

7.1.5 Component Restoration Curves

Restoration curves are developed based on a best fit to ATC-13 data (ATC, 1985) for the social function classifications of interest (SF 25a through SF 25e) consistent with damage states defined in the previous section (first four classes in ATC-13). Figure 7-1 shows restoration curves for urban and major roads, Figure 7-2 represents restoration curves for highway bridges, while Figure 7-3 shows restoration curves for highway tunnels. The smooth curves shown in these figures are normal curves characterized by a mean and a standard deviation. The parameters of these restoration curves are given in Table 7-3 and Table 7-4. The former table gives means and standard deviations for each restoration curve (i.e., smooth continuous curve), while the second table gives approximate discrete functions for the restoration curves as developed. Although not directly used in Hazus, the discretized restoration functions are presented here as guidance.

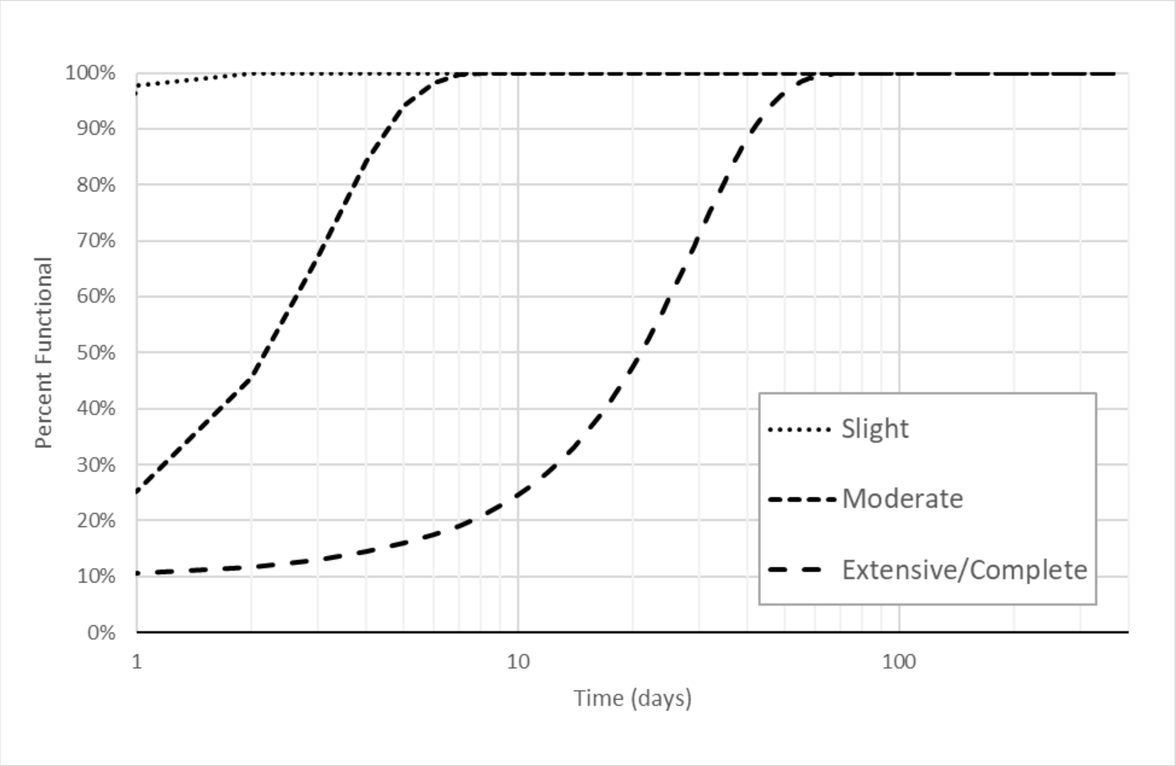


Figure 7-1 Restoration Curves for Urban and Major Roads

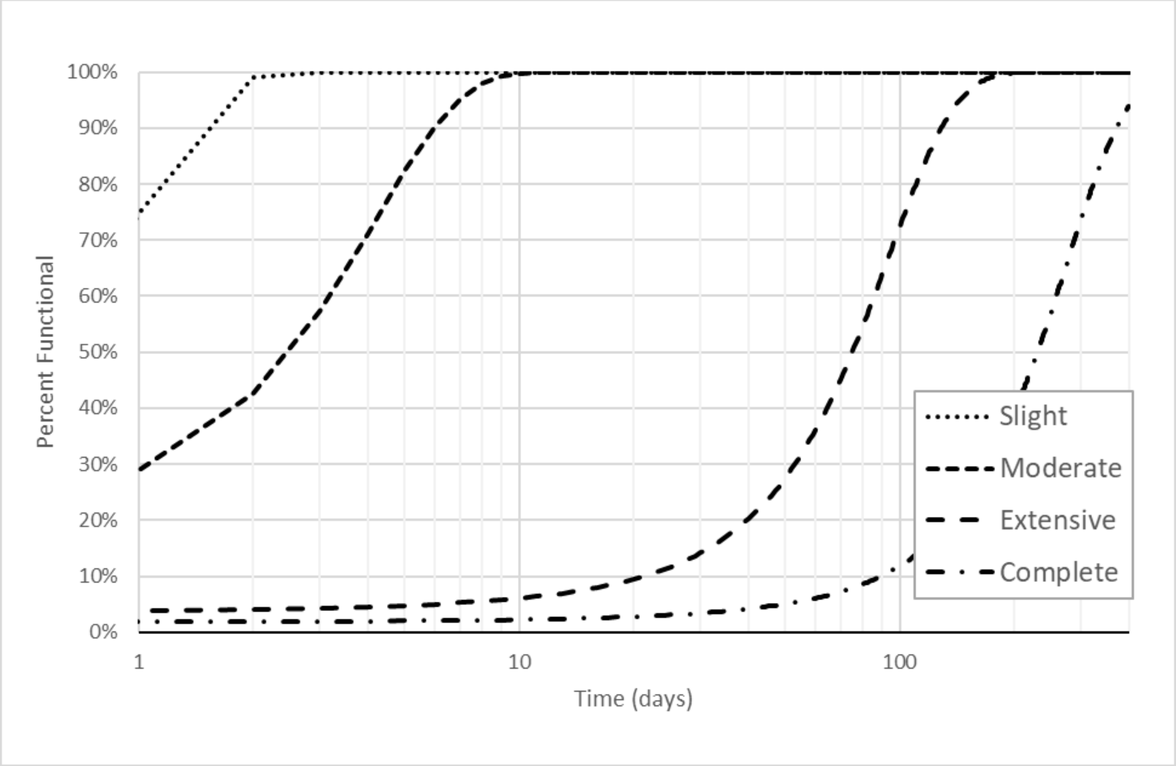


Figure 7-2 Restoration Curves for Highway Bridges

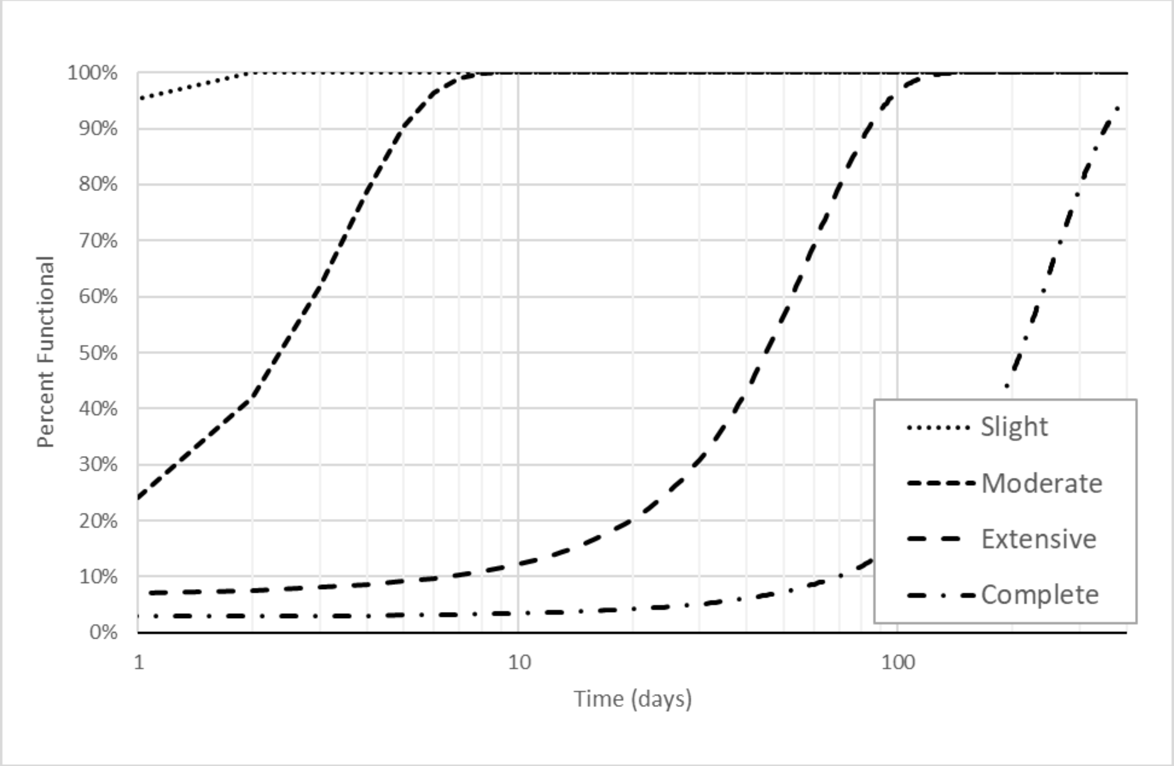


Figure 7-3 Restoration Curves for Highway Tunnels

Table 7-3 Continuous Restoration Functions for Highway System Components

Restoration Functions (All Normal Distributions)			
Classification	**Damage State**	**Mean (days)**	**σ (days)**
Roadways	Slight	0.9	0.05
	Moderate	2.2	1.8
	Extensive/Complete	21	16
Highway Bridges	Slight	0.6	0.6
	Moderate	2.5	2.7
	Extensive	75	42
	Complete	230	110
Tunnels	Slight	0.5	0.3
	Moderate	2.4	2.0
	Extensive	45	30
	Complete	210	110

The values shown in Table 7-4 below represent discrete restoration percentages based on damage state and restoration period based on damage state immediately after the earthquake. Although not directly used in Hazus, the discretized restoration functions are presented here as guidance.

Table 7-4 Discretized Restoration Functions for Highway System Components

Classification	Damage State	Functional Percentage				
		1 day	3 days	7 days	30 days	90 days
Roadways	Slight	90	100	100	100	100
	Moderate	25	65	100	100	100
	Extensive/Complete	10	14	20	70	100
Bridges	Slight	70	100	100	100	100
	Moderate	30	60	95	100	100
	Extensive	2	5	6	15	65
	Complete	0	2	2	4	10
Tunnels	Slight	90	100	100	100	100
	Moderate	25	65	100	100	100
	Extensive	5	8	10	30	95
	Complete	0	3	3	5	15

7.1.6 Development of Damage Functions

Fragility curves for highway system components are defined with respect to classification and ground motion or ground failure parameter.

7.1.6.1 Damage functions for Roadways

Fragility curves for major roads (HRD1) and urban roads (HRD2) are shown in Figure 7-4and Figure 7-5. The medians and dispersions of these curves are presented in Table 7-5.

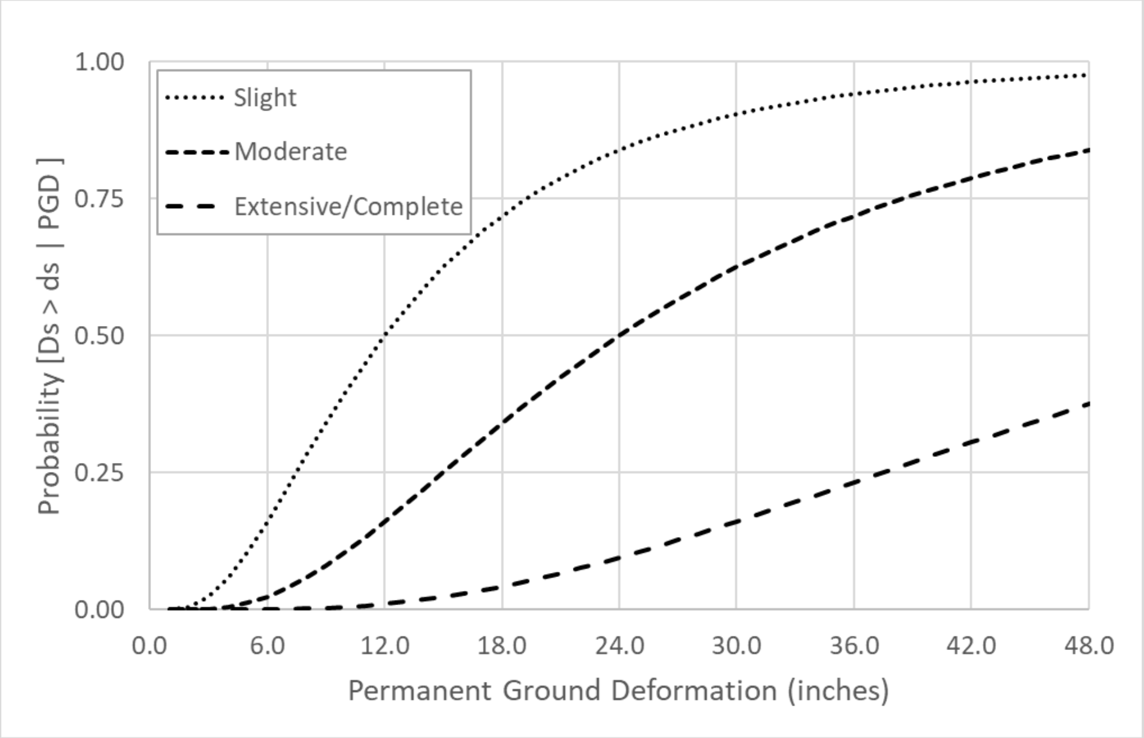


Figure 7-4 Fragility Curves at Various Damage States for Major Roads (Interstate and State Highways)

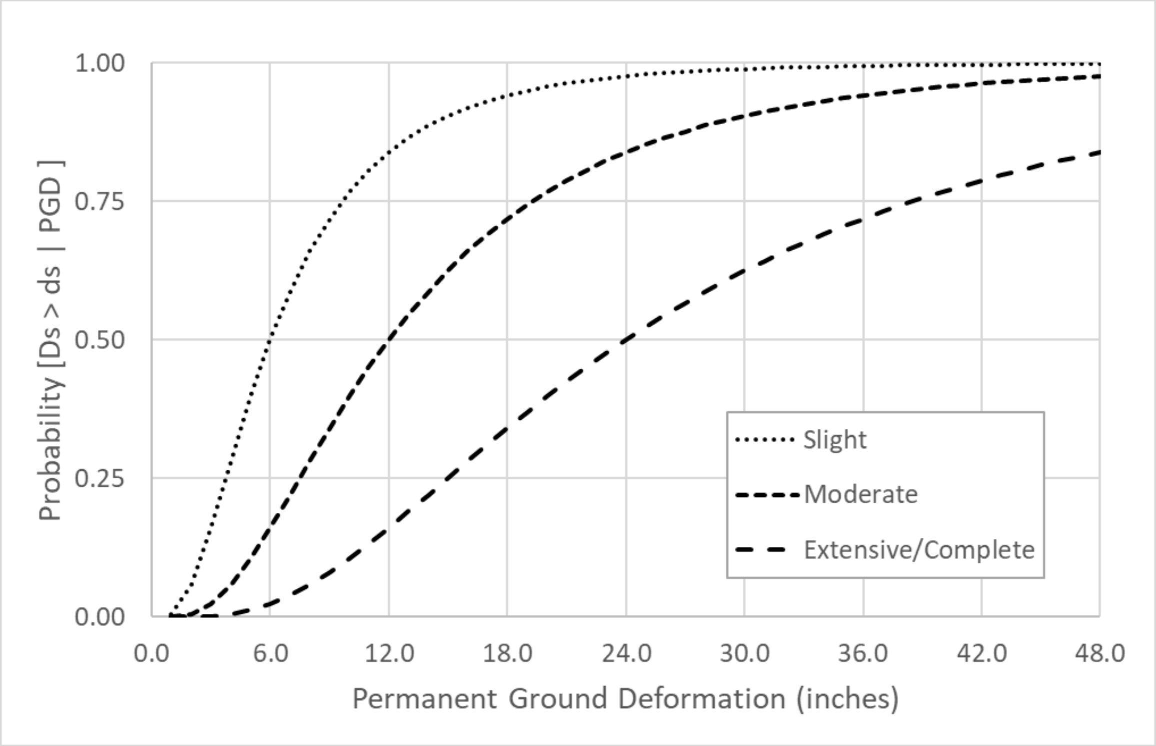


Figure 7-5 Fragility Curves at Various Damage States for Urban Roads

Table 7-5 Permanent Ground Deformation Fragility Function for Roadways

Components	Damage State	Median (in)	β
Major Road (HRD1)	Slight	12	0.7
	Moderate	24	0.7
	Extensive/Complete	60	0.7
Urban Roads (HRD2)	Slight	6	0.7
	Moderate	12	0.7
	Extensive/Complete	24	0.7

7.1.6.2 Damage Functions for Bridges

There are 28 primary bridge types for which all four damage states are identified and described. For other bridges, fragility curves of the 28 primary bridge types are adjusted to reflect the expected performance of a specific bridge which may be better or worse than the corresponding primary bridge type.

A total of 224 bridge damage functions are obtained, 112 for ground shaking and 112 for ground failure. For a complete description on the theoretical background of the damage functions, see Basoz and Mander (1999).

Medians of these damage functions are given in Table 7-6. The dispersion is set to 0.6 for the ground shaking fragility function and 0.2 for the ground failure fragility function. Only incipient unseating and collapse (i.e., which correspond to the Extensive and Complete damage states) are considered as possible types of damage due to ground failure. Initial damage to bearings (i.e., which would correspond to the Slight and/or Moderate damage states) from ground failure is not considered. Figure 7-6 and Figure 7-7 show example fragility curves for major bridges.

Table 7-6 Fragility Function Median Values for Highway Bridges

Class	Sa [1.0 sec in g's] for Damage Functions due to Ground Shaking				PGD [inches] for Damage Functions due to Ground Failure			
	Slight	Moderate	Extensive	Complete	Slight	Moderate	Extensive	Complete
HWB1	0.40	0.50	0.70	0.90	3.9	3.9	3.9	13.8
HWB2	0.60	0.90	1.10	1.70	3.9	3.9	3.9	13.8
HWB3	0.80	1.00	1.20	1.70	3.9	3.9	3.9	13.8
HWB4	0.80	1.00	1.20	1.70	3.9	3.9	3.9	13.8
HWB5	0.25	0.35	0.45	0.70	3.9	3.9	3.9	13.8
HWB6	0.30	0.50	0.60	0.90	3.9	3.9	3.9	13.8
HWB7	0.50	0.80	1.10	1.70	3.9	3.9	3.9	13.8
HWB8	0.35	0.45	0.55	0.80	3.9	3.9	3.9	13.8
HWB9	0.60	0.90	1.30	1.60	3.9	3.9	3.9	13.8
HWB10	0.60	0.90	1.10	1.50	3.9	3.9	3.9	13.8
HWB11	0.90	0.90	1.10	1.50	3.9	3.9	3.9	13.8
HWB12	0.25	0.35	0.45	0.70	3.9	3.9	3.9	13.8

Class	Sa [1.0 sec in g's] for Damage Functions due to Ground Shaking				PGD [inches] for Damage Functions due to Ground Failure			
	Slight	Moderate	Extensive	Complete	Slight	Moderate	Extensive	Complete
HWB13	0.30	0.50	0.60	0.90	3.9	3.9	3.9	13.8
HWB14	0.50	0.80	1.10	1.70	3.9	3.9	3.9	13.8
HWB15	0.75	0.75	0.75	1.10	3.9	3.9	3.9	13.8
HWB16	0.90	0.90	1.10	1.50	3.9	3.9	3.9	13.8
HWB17	0.25	0.35	0.45	0.70	3.9	3.9	3.9	13.8
HWB18	0.30	0.50	0.60	0.90	3.9	3.9	3.9	13.8
HWB19	0.50	0.80	1.10	1.70	3.9	3.9	3.9	13.8
HWB20	0.35	0.45	0.55	0.80	3.9	3.9	3.9	13.8
HWB21	0.60	0.90	1.30	1.60	3.9	3.9	3.9	13.8
HWB22	0.60	0.90	1.10	1.50	3.9	3.9	3.9	13.8
HWB23	0.90	0.90	1.10	1.50	3.9	3.9	3.9	13.8
HWB24	0.25	0.35	0.45	0.70	3.9	3.9	3.9	13.8
HWB25	0.30	0.50	0.60	0.90	3.9	3.9	3.9	13.8
HWB26	0.75	0.75	0.75	1.10	3.9	3.9	3.9	13.8
HWB27	0.75	0.75	0.75	1.10	3.9	3.9	3.9	13.8
HWB28	0.80	1.00	1.20	1.70	3.9	3.9	3.9	13.8

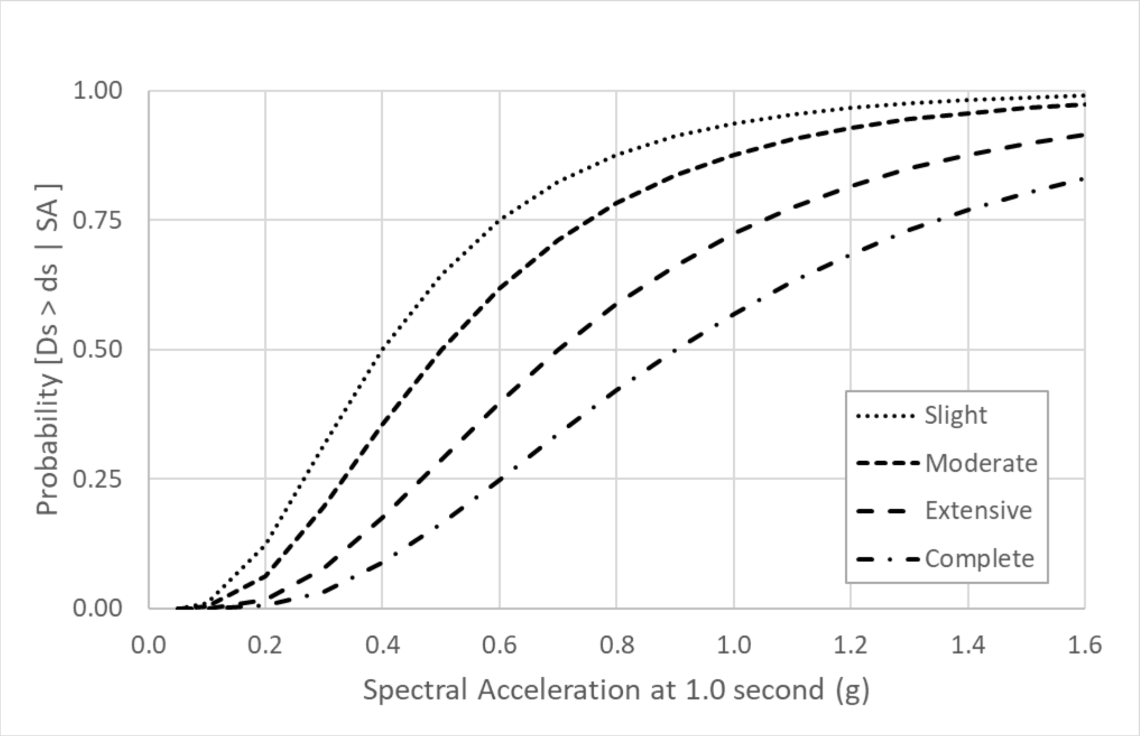


Figure 7-6 Fragility Curves for Conventionally Designed Major Bridges (HWB1)

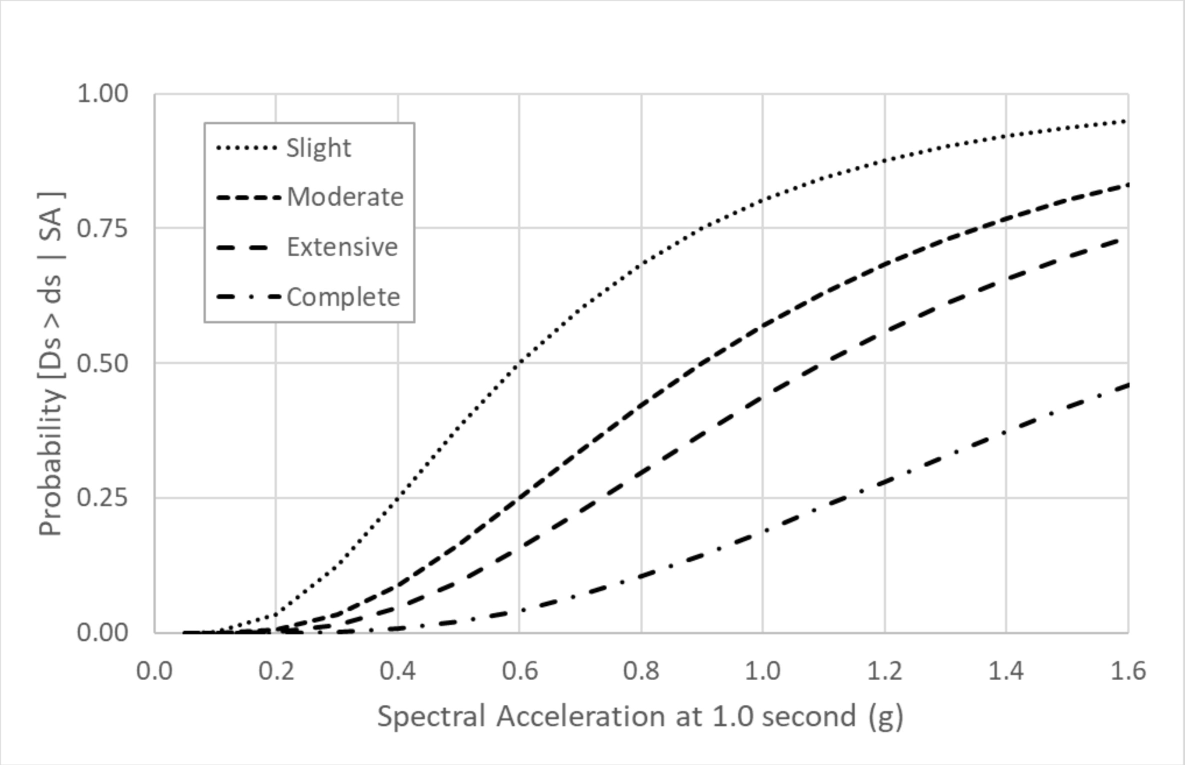


Figure 7-7 Fragility Curves for Seismically Designed Major Bridges (HWB2)

The damage algorithm for highway bridges can be broken into eight steps:

Step 1:

Get the bridge location (longitude and latitude), class (HWB1 through HWB28), number of spans (N), skew angle (α), span width (W), bridge length (L), and maximum span length (L_{max}). Note that the skew angle is defined as the angle between the centerline of a pier and a line normal to the roadway centerline.

Step 2:

Evaluate the soil-amplified shaking at the bridge site. That is, get the peak ground acceleration (PGA), spectral accelerations (Sa at 0.3 seconds and Sa at 1.0 second) and the permanent ground deformation (in inches).

Step 3:

Evaluate the following three modification factors:

Equation 7-1

$$\mathrm{K}_{\mathrm{skew}} = \sqrt{\sin(90-\propto)}$$

Equation 7-2

$$\mathrm{K}_{\mathrm{shape}} = \frac{2.5 * \mathrm{Sa}(1.0\ \mathrm{sec})}{\mathrm{Sa}(0.3\ \mathrm{sec})}$$

Equation 7-3

$$K_{3D} = \frac{1 + A}{N - B}$$

Where: A and B are read from Table 7-2

Step 4:

Modify the ground shaking medians for the "standard" fragility curves in Table 7-6 as follows:

Equation 7-4

$$\text{New Median [for slight]} = \text{Old Median [for slight]} * \text{Factor}_{\text{slight}}$$

Where:

$\text{Factor}_{\text{slight}}$ is 1 if Ishape = 0 (Ishape is read from Table 7-1)

Or

$\text{Factor}_{\text{slight}}$ minimum of (1, Kshape) if Ishape = 1

$$\text{New median [Moderate]} = \text{Old median [for Moderate]} * (K_{\text{skew}}) * (K_{3D})$$

$$\text{New median [Extensive]} = \text{Old median [for Extensive]} * (K_{\text{skew}}) * (K_{3D})$$

$$\text{New median [Complete]} = \text{Old median [for Complete]} * (K_{\text{skew}}) * (K_{3D})$$

Step 5:

Use the new medians along with the dispersion β = 0.6 to evaluate the ground shaking-related damage state probabilities. Note that Sa(1.0 sec) (listed in Table 7-6) is the parameter to use in this evaluation.

Step 6:

Modify the PGD medians for the "standard" fragility curves listed in Table 7-6 as follows

New PGD median [Moderate] = Table 7-6 PGD median [for Moderate] * f_1

New PGD median [Extensive] = Table 7-6 PGD median [for Extensive] * f_1

New PGD median [Complete] = Table 7-6 PGD median [for Complete] * f_2

Where f_1 and f_2 are modification factors that are functions of the number of spans (N), width of the span (W), length of the bridge (L), and the skewness (α) and can be computed using the equations in Table 7-7 below.

Table 7-7 Modifiers for PGD Medians

Class	f_1	f_2
HWB1	1	1
HWB2	1	1
HWB3	1	1
HWB4	1	1

Class	f_1	f_2
HWB5	$\frac{0.5L}{N * W * \sin(\alpha)}$	$\frac{0.5L}{N * W * \sin(\alpha)}$
HWB6	$\frac{0.5L}{N * W * \sin(\alpha)}$	$\frac{0.5L}{N * W * \sin(\alpha)}$
HWB7	$\frac{0.5L}{N * W * \sin(\alpha)}$	$\frac{0.5L}{N * W * \sin(\alpha)}$
HWB8	1	$\sin(\propto)$
HWB9	1	$\sin(\propto)$
HWB10	1	$\sin(\propto)$
HWB11	1	$\sin(\propto)$
HWB12	$\frac{0.5L}{N * W * \sin(\alpha)}$	$\frac{0.5L}{N * W * \sin(\alpha)}$
HWB13	$\frac{0.5L}{N * W * \sin(\alpha)}$	$\frac{0.5L}{N * W * \sin(\alpha)}$
HWB14	$\frac{0.5L}{N * W * \sin(\alpha)}$	$\frac{0.5L}{N * W * \sin(\alpha)}$
HWB15	1	$\sin(\propto)$
HWB16	1	$\sin(\propto)$
HWB17	$\frac{0.5L}{N * W * \sin(\alpha)}$	$\frac{0.5L}{N * W * \sin(\alpha)}$
HWB18	$\frac{0.5L}{N * W * \sin(\alpha)}$	$\frac{0.5L}{N * W * \sin(\alpha)}$
HWB19	$\frac{0.5L}{N * W * \sin(\alpha)}$	$\frac{0.5L}{N * W * \sin(\alpha)}$
HWB20	1	$\sin(\propto)$
HWB21	1	$\sin(\propto)$
HWB22	$\frac{0.5L}{N * W * \sin(\alpha)}$	$\frac{0.5L}{N * W * \sin(\alpha)}$
HWB23	$\frac{0.5L}{N * W * \sin(\alpha)}$	$\frac{0.5L}{N * W * \sin(\alpha)}$
HWB24	$\frac{0.5L}{N * W * \sin(\alpha)}$	$\frac{0.5L}{N * W * \sin(\alpha)}$
HWB25	$\frac{0.5L}{N * W * \sin(\alpha)}$	$\frac{0.5L}{N * W * \sin(\alpha)}$
HWB26	1	$\sin(\propto)$
HWB27	1	$\sin(\propto)$
HWB28	1	1

Step 7:

Use the new medians along with the dispersion β = 0.2 to evaluate ground failure-related damage state probabilities.

Step 8:

Combine the damage state probabilities and evaluate functionality of bridge.

Example of bridge damage evaluation:

Consider a three-span simply supported prestressed concrete bridge seated on neoprene bearings located in the Memphis area. Table 7-8 lists the data for this bridge obtained from NBI. For the scenario earthquake, assume that the ground motion for rock conditions (NEHRP class B) is defined by the following parameters:

Where:

Sa(0.3 sec) = 2.1g

Sa(1.0 sec) = 0.24g

PGA = 0.38g

Also, assume that the bridge is located in soil type D.

The median spectral acceleration ordinates for different damage states are determined as follows:

Step 1:

Ground motion data is amplified for soil conditions (as given in Table 4-7):

Sa(0.3 sec) = 1.0 * 2.1g = 2.1g

Sa(1.0 sec) = 1.8 * 2.4g = 0.43g

PGA = 1.4 * 0.38g = 0.53g

Step 2:

The bridge class is determined. Based on the information in Table 7-8, HWB17 is determined to be the bridge class.

Table 7-8 Bridge Data Required for the Example Analysis

NBI field	Data	Remarks
27	1968	Year built
34	32	Angle of skew
43	501	Prestressed concrete, simple span
45	3	Number of spans
48	23	Maximum span length (m)
49	56	Total bridge length (m)

Step 3:

Parameters needed in evaluating the median spectral accelerations are computed:

Equation 7-5

$$\mathrm{K}_{\mathrm{skew}} = \sqrt{}\sin(90-\propto) = \sqrt{}\sin(90-32) = 0.91$$

Equation 7-6

$$K_{shape} = \frac{2.5 * Sa(1.0\ sec)}{Sa(0.3\ sec)} = 0.50$$

Equation 7-7

$$K_{3D} = \frac{1 + A}{N - B} = \frac{1 + 0.25}{3 - 1} = 1.125$$

Step 4:

From Table 7-1, Ishape is 0 for HWB17, therefore “long periods” govern, and $Factor_{slight}$ is 1.

Therefore:

New Sa 1.0 sec median [Slight] = Old Sa 1.0 median [Slight] * $Factor_{slight}$

New Sa 1.0 sec median [Moderate] = Old Sa 1.0 median [Moderate] * K_{skew} * K_{3D}

New Sa 1.0 sec median [Extensive] = Old Sa 1.0 median [Extensive] * K_{skew} * K_{3D}

New Sa 1.0 sec median [Complete] = Old Sa 1.0 median [Complete] * K_{skew} * K_{3D}

Medians are noted in Equation 7-4.

Step 5:

With these new medians, the shaking-related discrete damage state probabilities are (using lognormal functions with the above medians and with betas equal to 0.6):

P [None] = 1 – 0.82 = 0.18

P [Slight] = 0.82 – 0.62 = 0.20

P [Moderate] = 0.62 – 0.46 = 0.16

P [Extensive] = 0.46 – 0.20 = 0.26

P [Complete] = 0.20

7.1.6.3 Damage Functions for Tunnels

The tunnel damage functions are based on the damage potential of their subcomponents, namely the liner and the portal (G&E, 1994a). G&E findings are based partly on earthquake experience data reported by Dowding et al. (1978) and Owen et al. (1981). Further information on the tunnel subcomponent fragilities, can be found in Appendix A.

From the subcomponent damage functions, ten tunnel fragility functions were developed, four for ground shaking (PGA) and six for permanent ground failure. Medians and dispersion factors for these fragility functions are given in Table 7-9. Graphical representations of these damage functions are also provided; Figure 7-8 and Figure 7-9 plot fragility curves due to PGA for bored/drilled and cut & cover tunnels, respectively, while Figure 7-10 presents fragility curves for tunnels due to PGD.

Table 7-9 Peak Ground Acceleration Fragility Functions for Tunnels

Subcomponents	Damage State	Median (g)	β
Bored/Drilled (HTU1)	Slight	0.6	0.6
	Moderate	0.8	0.6
Cut & Cover (HTU2)	Slight	0.5	0.6
	Moderate	0.7	0.6
Bored/Drilled (HTU1)	Slight	6.0	0.7
	Moderate	12.0	0.5
	Extensive/Complete	60.0	0.5
Cut & Cover (HTU2)	Slight	6.0	0.7
	Moderate	12.0	0.5
	Extensive/Complete	60.0	0.5

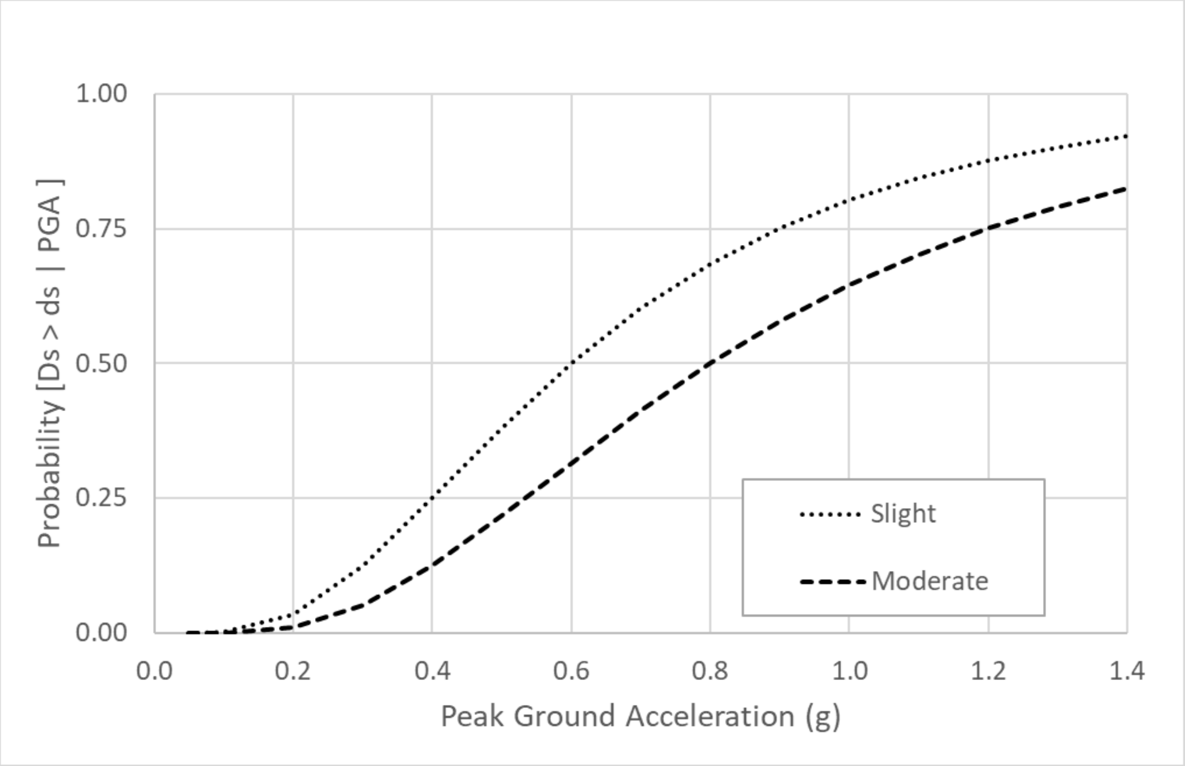


Figure 7-8 Fragility Curves at Various Damage States for Bored/Drilled Tunnels Subject to Peak Ground Acceleration

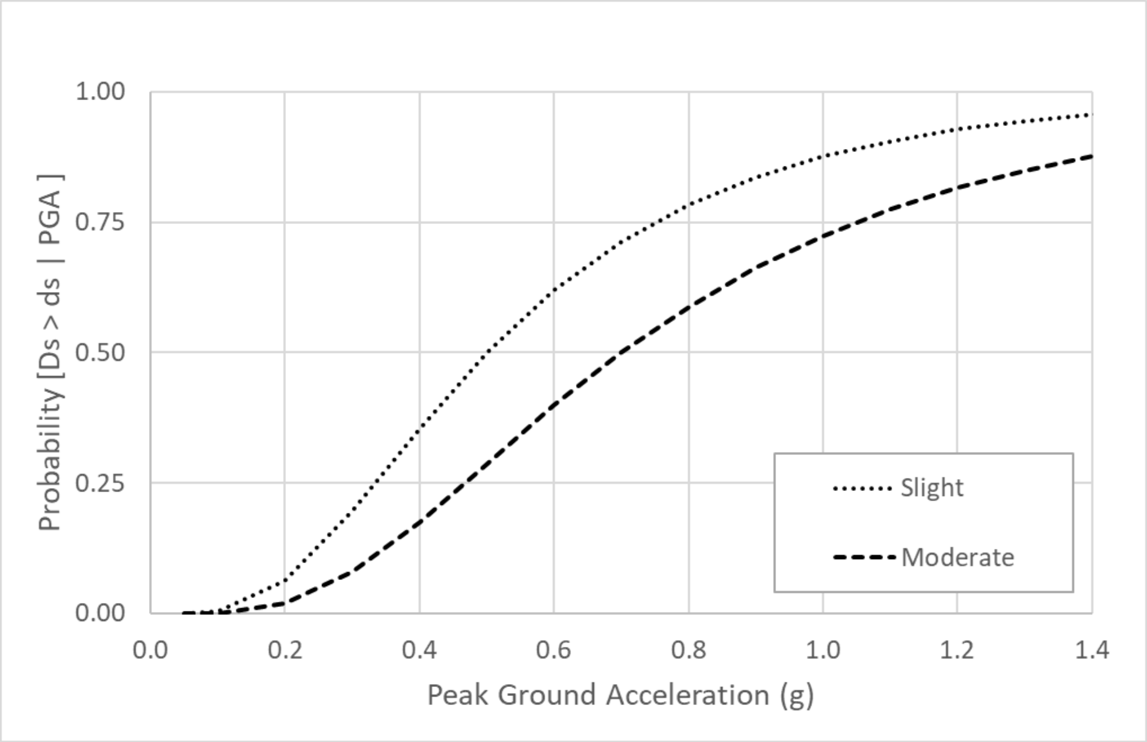


Figure 7-9 Fragility Curves at Various Damage States for Cut & Cover Tunnels Subject to Peak Ground Acceleration

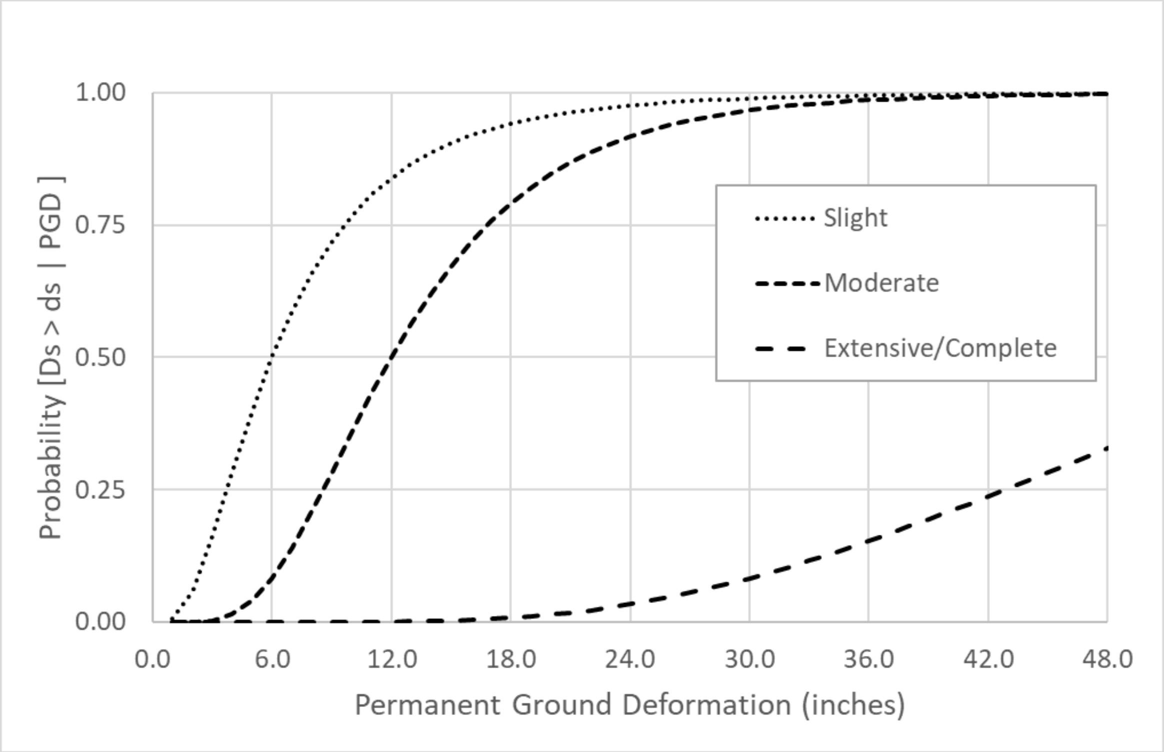


Figure 7-10 Fragility Curves at Various Damage States for All Types of Tunnels Subject to Permanent Ground Deformation

7.1.7 Guidance for Loss Estimation Using Advanced Data and Models Analysis

For an advanced analysis, experts can use the methodology developed with the flexibility to include a more refined inventory of the transportation system pertaining to the study area. For example, specific data on highway bridge seismic retrofits can be used to modify class from conventional to seismic.

7.2 Railway Transportation System

This section presents an earthquake loss estimation methodology for a railway transportation system. This system consists of tracks/roadbeds, bridges, tunnels, urban stations, maintenance facilities, fuel facilities, and dispatch facilities. Past earthquake damage reveals that bridges, tunnels, urban stations, maintenance facilities, fuel facilities, and dispatch facilities are vulnerable to both ground shaking and ground failure, while railway tracks/roadbeds are significantly affected by ground failure alone. Railway tracks located on soft soil or fill or tracks which cross a surface fault rupture can experience failure resulting in loss of functionality. Railway bridges that fail usually result in significant disruption to the transportation network, especially bridges that cross waterways. Likewise, railway tunnels are often not redundant, and major disruption to the transportation system is likely to occur should a tunnel become non-functional.

The scope of this section includes development of methods for estimation of earthquake damage to a railway transportation system given knowledge of the system's components (i.e., tracks, bridges, tunnels, stations, maintenance facilities, fuel facilities, or dispatch facilities), the classification of each component (e.g., for fuel facilities, whether the equipment within the facility is anchored or not), and the hazards (i.e., peak ground acceleration and permanent ground deformation).

Damage states describing the level of damage to each railway system component are defined (i.e., None, Slight, Moderate, Extensive, or Complete). Damage states are related to damage ratio (defined as ratio of repair to replacement cost) for evaluation of direct economic loss. Fragility curves are developed for each type of railway system component. These curves describe the probability of reaching or exceeding each damage state given the level of ground motion or ground displacement.

Evaluation of component functionality is done in a manner similar to that of highway components. Component restoration curves are provided for each damage state to evaluate loss of function. Restoration curves describe the fraction or percentage of the component that is expected to be open or operational as a function of time following the earthquake. For example, an extensively damaged railway facility might be closed (0% functional) immediately following the earthquake, but 100% functional after 30 days.

Interdependence of components on the overall system functionality is not addressed by the methodology. Such considerations require a system (network) analysis.

7.2.1 Input Requirements and Output Information

Required input to estimate damage to railway systems includes the following items:

- Track and Roadbeds
    - Geographical location of railway links (polyline segments)
    - Permanent ground deformation (PGD) at trackbed link

- Railway Bridges
    - Bridge classification
    - Geographical location of bridge (longitude and latitude)
    - Spectral Acceleration at 0.3 and 1.0 seconds and PGD at bridge
- Railway Tunnels
    - Tunnel classification
    - Geographical location of tunnels (longitude and latitude)
    - Peak ground acceleration (PGA) and PGD at tunnel
- Railway System Facilities
    - Facility classification
    - Geographical location of facilities (longitude and latitude)
    - PGA and PGD at facility

Direct damage output for railway systems includes probability estimates of (1) component functionality and (2) physical damage, expressed in terms of the component's damage ratio. Damage ratios are used as inputs to the direct economic loss module (see Section 11).

Component functionality is described in a manner similar to highway system components, that is, by the probability of being in a damage state (immediately following the earthquake) and by the associated fraction or percentage of the component that is expected to be functional after a specified period of time.

7.2.2 Form of Damage Functions

Damage functions or fragility curves for all railway system components described below are modeled as lognormal functions that give the probability of reaching or exceeding different levels of damage for a given level of ground motion or ground failure. Each fragility curve is characterized by a median value of ground motion (or failure) and an associated dispersion factor (lognormal standard deviation). Ground motion is quantified in terms of PGA and spectral acceleration (Sa) and ground failure is quantified in terms of permanent ground displacement.

- For tracks/roadbeds, fragility curves are defined in terms of PGD
- For railway bridges, fragility curves are defined similarly to those for highway bridges
- For tunnels, fragility curves are the same as defined for highway systems (in terms of PGA and PGD)
- For railway system facilities, fragility curves are defined in terms of PGA or SA and PGD

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

7.2.3 Description of Railway System Components

A railway system consists of four components: tracks/roadbeds, bridges, tunnels, and facilities. This section provides a brief description of each.

- *Tracks/Roadbeds*: Tracks/roadbeds refers to the assembly of rails, ties, and fastenings, and the ground on which they rest. Only one classification is adopted for these components. This classification is analogous to that of urban roads in highway systems.

- *Bridges*: Railway bridges are classified in a manner similar to steel and concrete highway bridges.
- *Tunnels*: Railway tunnels follow the same classification as highway tunnels. That is, they are classified either as bored/drilled tunnels, or cut and cover tunnels.
- *Railway system facilities*: Railway system facilities include urban and suburban stations, maintenance facilities, fuel facilities, and dispatch facilities.
    - Urban and suburban stations are generally key connecting hubs that are important for system functionality. In the western US, these buildings are mostly made of reinforced concrete shear walls or moment resisting steel frames, while in the eastern US, the small stations are mostly wood, and the large ones are mostly masonry or braced steel frames.
    - Maintenance facilities are housed in large structures that are not usually critical for system functionality as maintenance activities can be delayed or performed elsewhere. These building structures are often made of steel braced frames.
    - Fuel facilities include buildings, tanks (anchored, unanchored, or buried), backup power systems (if available, anchored or unanchored diesel generators), pumps, and other equipment (anchored or unanchored). It should be mentioned that anchored equipment in general refers to equipment designed with special seismic tiedowns or tiebacks, while unanchored equipment refers to equipment designed with no special considerations other than the manufacturer's normal requirements. While some vibrating components, such as pumps, are bolted down regardless of concern for earthquakes, as used here "anchored" means all components have been engineered to meet seismic criteria which may include bracing (e.g., pipe or stack bracing) or flexibility requirements (e.g., flexible connections across separation joints) as well as anchorage. These definitions of anchored and unanchored apply to all transportation system components. Above ground tanks are typically made of steel with roofs also made of steel. Buried tanks are typically concrete wall construction with concrete roofs. The fuel facility functionality module was determined with a fault tree analysis considering redundancies and subcomponent behavior. Note that generic building damage functions were used in this fault tree analysis to develop the overall fragility curve of fuel facilities. In total, five types of fuel facilities are considered. These are: fuel facilities with or without anchored equipment, with or without backup power (all combinations), and fuel facilities with buried tanks.
    - Dispatch facilities consist of buildings, backup power supplies (if available, anchored or unanchored diesel generators), and electrical equipment (anchored or unanchored). Damage functions for a generic reinforced concrete building with shear walls were used in this fault tree to develop the overall fragility curves for dispatch facilities. In total, four types of dispatch facilities are considered. These are: dispatch facilities with or without anchored equipment and with or without backup power (all combinations).

7.2.4 Definitions of Damage States

A total of five damage states are defined for railway system components. These are None, Slight, Moderate, Extensive, and Complete.

Slight Damage

- For tracks and roadbeds, Slight damage is defined by minor (localized) derailment due to slight differential settlement of embankment or offset of the ground.
- For railway bridges, Slight damage is defined similarly to highway bridges (see Section 7.1.4).
- For railway tunnels, Slight damage is defined similarly to highway tunnels (see Section 7.1.4).
- For railway system facilities:
    - For urban stations and maintenance facilities, whose performance is governed by the performance of the buildings themselves, the Slight damage state is defined as Slight building damage.
    - For fuel facilities with anchored equipment, Slight damage is defined by slight damage to the pump building, minor damage to the anchorage of tanks, or loss of off-site power for a very short period of time and minor damage to backup power (i.e., to diesel generators, if available).
    - For fuel facilities with unanchored equipment, Slight damage is defined by elephant’s foot buckling of tanks with no leakage or loss of contents, slight damage to the pump building, or loss of commercial power for a very short period of time and minor damage to backup power (i.e., to diesel generators, if available).
    - For fuel facilities with buried tanks (PGD related damage), Slight damage is defined by minor uplift (a few inches) of the buried tanks or minor cracking of concrete walls.
    - For dispatch facilities with anchored equipment, Slight damage is defined by minor damage to equipment anchorage, slight damage to the building, or loss of commercial power for a very short period of time and minor damage to backup power (i.e., diesel generators, if available).
    - For dispatch facilities with unanchored equipment, Slight damage is defined by loss of off-site power for a very short period of time and minor damage to backup power (i.e., to diesel generators, if available), or slight damage to the building.

Moderate Damage

- For railway tracks and roadbeds, Moderate damage is defined by considerable derailment due to differential settlement or offset of the ground. Rail repair is required.
- For railway bridges, Moderate damage is defined similarly to highway bridges.
- For railway tunnels, Moderate damage is defined similarly to highway tunnels
- For railway system facilities:
    - For urban stations and maintenance facilities, Moderate damage is defined as moderate building damage.
    - For fuel facilities with anchored equipment, Moderate damage is defined by elephant’s foot buckling of tanks, with no leakage or loss of contents, considerable damage to equipment, and moderate damage to the pump building, or loss of commercial power for a few days and malfunction of backup power (i.e., diesel generators, if available).

  - For fuel facilities with unanchored equipment, Moderate damage is defined by elephant's foot buckling of tanks with partial loss of contents, moderate damage to the pump building, loss of commercial power for a few days and malfunction of backup power (i.e., diesel generators, if available).
  - For fuel facilities with buried tanks, Moderate damage is defined by damage to roof supporting columns, and considerable cracking of the walls.
  - For dispatch facilities with anchored equipment, Moderate damage is defined by considerable damage to equipment anchorage, moderate damage to the building, or loss of commercial power for a few days and malfunction of backup power (i.e., diesel generators, if available).
  - For dispatch facilities with unanchored equipment, Moderate damage is defined by moderate damage to the building, or loss of off-site power for a few days and malfunction of backup power (i.e., diesel generators, if available).

Extensive Damage

- For railway tracks/roadbeds, Extensive damage is defined by major differential settlement of the ground resulting in potential derailment over an extended length of track.
- For railway bridges, extensive damage is defined similarly to highway bridges.
- For railway tunnels, is defined similarly to highway tunnels.
- For railway system facilities:
  - For urban stations and maintenance facilities, is defined as extensive building damage.
  - For fuel facilities with anchored equipments defined by elephant's foot buckling of tanks with loss of contents, extensive damage to pumps (cracked/sheared shafts), or extensive damage to the pump building.
  - For fuel facilities with unanchored equipment, extensive damage is defined by weld failure at the base of the tank with loss of contents, extensive damage to the pump building, or extensive damage to the pumps (cracked/sheared shafts).
  - For fuel facilities with buried tanks, extensive damage is defined by considerable uplift (more than a foot) of the tanks and rupture of the attached piping.
  - For dispatch facilities with unanchored or anchored equipment, extensive damage is defined by extensive building damage; at this level of damage, the performance of the building governs the facility's overall damage state.

Complete Damage

- For railway tracks/roadbeds, Complete damage is the same as Extensive damage.
- For railway bridges, Complete damage is defined similarly to highway bridges.
- For railway tunnels, Complete damage is defined similarly to highway tunnels.
- For railway system facilities:
  - For urban stations and maintenance facilities, Complete damage is defined as complete building damage.

- For fuel facilities with anchored equipment, Complete damage is defined by weld failure ase of the tank with loss of contents, or complete damage to the pump building.
- For fuel facilities with unanchored equipment, Complete damage is defined by tearing of the tank wall or implosion of the tank (with total contents), or complete damage to the pump building.
- For fuel facilities with buried tanks, Complete damage is same as Extensive damage.
- For dispatch facilities with unanchored or anchored equipment, Complete damage is same as Extensive damage.

7.2.5 Component Restoration Curves

Restoration curves were developed based in part on ATC-13 damage data (ATC, 1985) for the social function classifications of interest (SF 26a through SF 26d) consistent with damage states defined in the previous section. Normally distributed functions are used to approximate these restoration curves, as was done for highway systems. Means and dispersions (standard deviations) of these restoration functions are given in Table 7-10 and Table 7-11 gives approximate discrete functions for these restoration functions. Although not directly used in Hazus, the discretized restoration functions are presented here as guidance. ATC-13 restoration data for railway terminal stations are used to generically represent all other railway facilities.

Table 7-10 Continuous Restoration Functions for Railway System Components (All Normal Distributions)

Classification	Damage State	Mean (days)	σ (days)
Railway Tracks	Slight	0.9	0.07
	Moderate	3.3	3.0
	Extensive	15	13
	Complete	65	45
Railway Bridges	Slight	0.6	0.6
	Moderate	2.5	2.7
	Extensive	75	42
	Complete	230	110
Railway Tunnels	Slight	0.9	0.05
	Moderate	4.0	3.0
	Extensive	37	30
	Complete	150	80
Railway Facilities – Fuel Facilities	Slight	0.9	0.05
	Moderate	1.5	1.5
	Extensive	15	15
	Complete	65	50
Railway Facilities – Stations, Dispatch and Maintenance Facilities	Slight	0	0
	Moderate	1.5	1.5
	Extensive	50	50
	Complete	150	120

Table 7-11 Discretized Restoration Functions for Railway System Components

Classification	Damage State	Functional Percentage				
		1 day	3 days	7 days	30 days	90 days
Railway Tracks	Slight	90	100	100	100	100
	Moderate	22	46	90	100	100
	Extensive	14	18	28	87	100
	Complete	6	8	10	22	70
Railway Bridges	Slight	80	100	100	100	100
	Moderate	15	55	100	100	100
	Extensive	9	10	14	50	100
	Complete	7	7	8	14	40
Railway Tunnels	Slight	95	100	100	100	100
	Moderate	16	38	85	100	100
	Extensive	11	13	16	40	97
	Complete	3	4	4	7	22
Railway Facilities	Slight	95	100	100	100	100
	Moderate	37	85	100	100	100
	Extensive	15	20	29	83	100
	Complete	10	11	12	25	70

7.2.6 Development of Damage Functions

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

Fragility functions for tracks/roadbeds are similar to those of major roads (see Section 7.1.6.1). The medians and dispersions of these curves were given in Table 7-5. Fragility curves for rail bridges are the same as those presented for single span highway bridges (HWB3 and HWB4 in Section 7.1.6.2. for highway bridges). Although Hazus provides 11 rail bridge classes, unique fragility curves for each are not provided, however, the classification allows for future enhancements by the program or for the advanced user should they have developed additional unique fragilities. Tunnel damage functions are the same as those derived for highway tunnels (see Section 7.1.6.3). These were given in Table 7-9 and plotted in Figure 7-8, Figure 7-9, and Figure 7-10.

7.2.6.1 Damage Functions for Railway System Facilities

Damage functions for railway system facilities are defined in terms of spectral acceleration values and PGD. Note that, unless otherwise specified, permanent ground failure-related damage functions for these facilities are assumed to be similar to those described for buildings. These are:

- For lateral spreading, a lognormal damage function with a median of 60 inches and a dispersion of 1.2 is assumed for the damage state of “at least Extensive”. 20% of this damage is assumed to be Complete. That is, for a PGD of 60 inches due to lateral spreading, there is a 50% probability of “at least Extensive” damage.
- For vertical settlement, a lognormal curve with a median of 10 inches and a dispersion of 1.2 is assumed for the damage state of “at least Extensive”. 20% of this damage is

assumed to be Complete. That is, for a PGD of 10 inches due to vertical settlement, there is a 50% chance of “at least Extensive” damage.

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

An example of how to combine multiple PGD damage state probability distributions with a PGA damage state probability distribution is presented in Section 7.2.6.2.

Damage functions for urban stations and maintenance facilities are similar to standard building fragility curves discussed in Section 5.

7.2.6.1.1 Damage Functions for Fuel Facilities

Fragility curves are developed for the five types of fuel facilities mentioned before, namely, fuel facilities with anchored equipment and backup power, fuel facilities with anchored equipment but no backup power, fuel facilities with unanchored equipment and backup power, fuel facilities with unanchored equipment and no backup power, and fuel facilities with buried tanks. The fuel facility fragility functions are based on the damage potential of their subcomponents (i.e., the pump building, electric power, tanks, and other equipment). A generic building type is used in developing the fragility curves for fuel facilities in the specified fault tree logic. Note that interaction effects, specifically that of electric power, are considered in this fault tree logic for the Slight and Moderate damage states. Further information on the fuel facility subcomponent fragilities can be found in Appendix A.

Component fragility curves are obtained using the methodology wherein a lognormal curve that best fits the results of the Boolean combination is determined numerically. It should be mentioned that the Boolean logic is implicitly presented within the definition of a particular damage state.

The fault tree shown in Figure 7-11 presents the Boolean logic for the case of moderate damage to fuel facilities with anchored equipment and backup power, while Figure 7-12 provides the fragility curve resulting from the Boolean combination to the fitted lognormal fragility curve. The dotted line in Figure 7-12 represents the overall fuel facility fragility curve.

The medians and dispersions of the damage functions for anchored and unanchored fuel facilities, and facilities with buried tanks are shown in Table 7-12 and Table 7-13. These damage functions are also shown as fragility curves in Figure 7-13 through Figure 7-17. Damage functions available within Hazus are the functions for facilities with unanchored components. Users wishing to analyze facilities with anchored components could revise the existing damage functions through the Hazus menus.

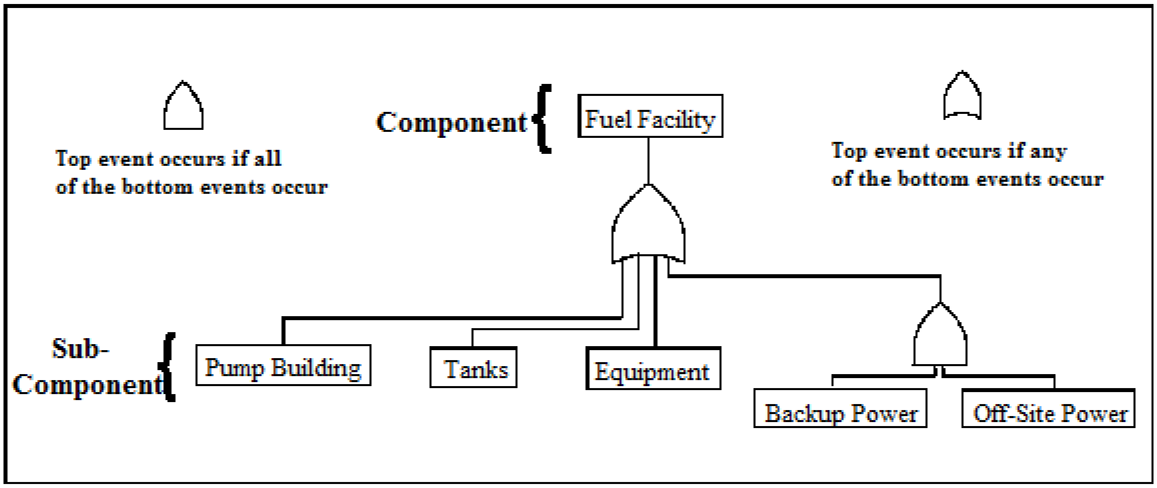


Figure 7-11 Fault Tree for Moderate Damage to Fuel Facilities with Anchored Equipment and Backup

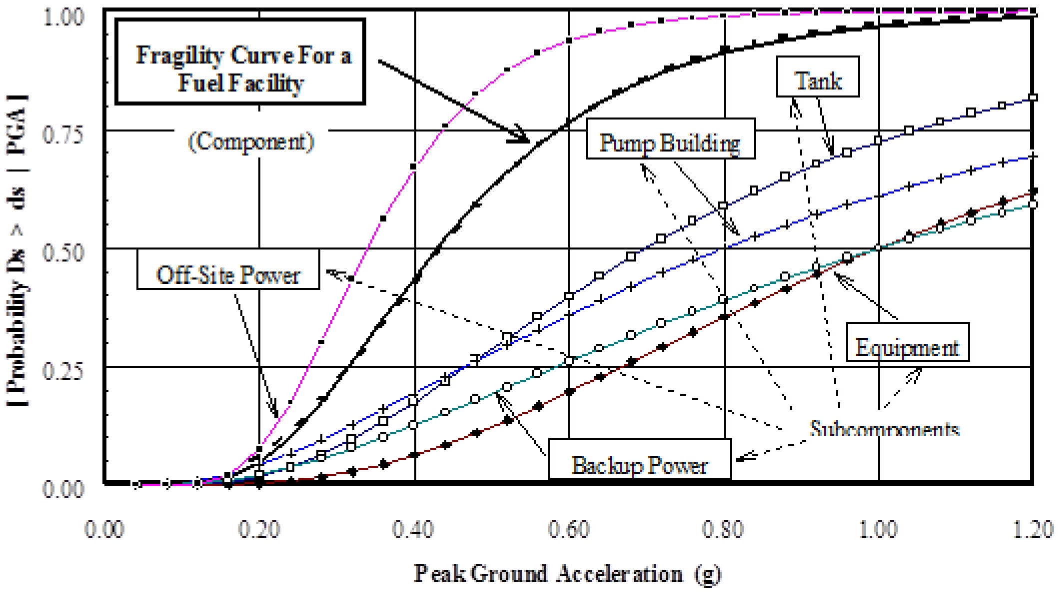


Figure 7-12 Example of Fitting a Lognormal Curve to a Fuel Facility Fragility Curve

Table 7-12 Peak Ground Acceleration Fragility Functions for Fuel Facilities

Classification	Damage State	Median (g)	β
Facility with Anchored Components w/Backup Power	Slight	0.23	0.50
	Moderate	0.43	0.45
	Extensive	0.64	0.60
	Complete	1.10	0.60
Facility with Anchored Components w/o Backup Power	Slight	0.12	0.55
	Moderate	0.27	0.50
	Extensive	0.64	0.60
	Complete	1.10	0.60

Classification	Damage State	Median (g)	β
Facility with Unanchored Components w/ Backup Power	Slight	0.10	0.55
	Moderate	0.23	0.50
	Extensive	0.48	0.60
	Complete	0.80	0.60
Facility with Unanchored Components w/o Backup Power	Slight	0.09	0.50
	Moderate	0.20	0.45
	Extensive	0.48	0.60
	Complete	0.80	0.60

Table 7-13 Peak Ground Deformation Fragility Functions for Fuel Facilities

Classification	Damage State	Median (g)	β
Fuel facility w/ buried tanks	Slight	4	0.5
	Moderate	8	0.5
	Extensive/Complete	24	0.5

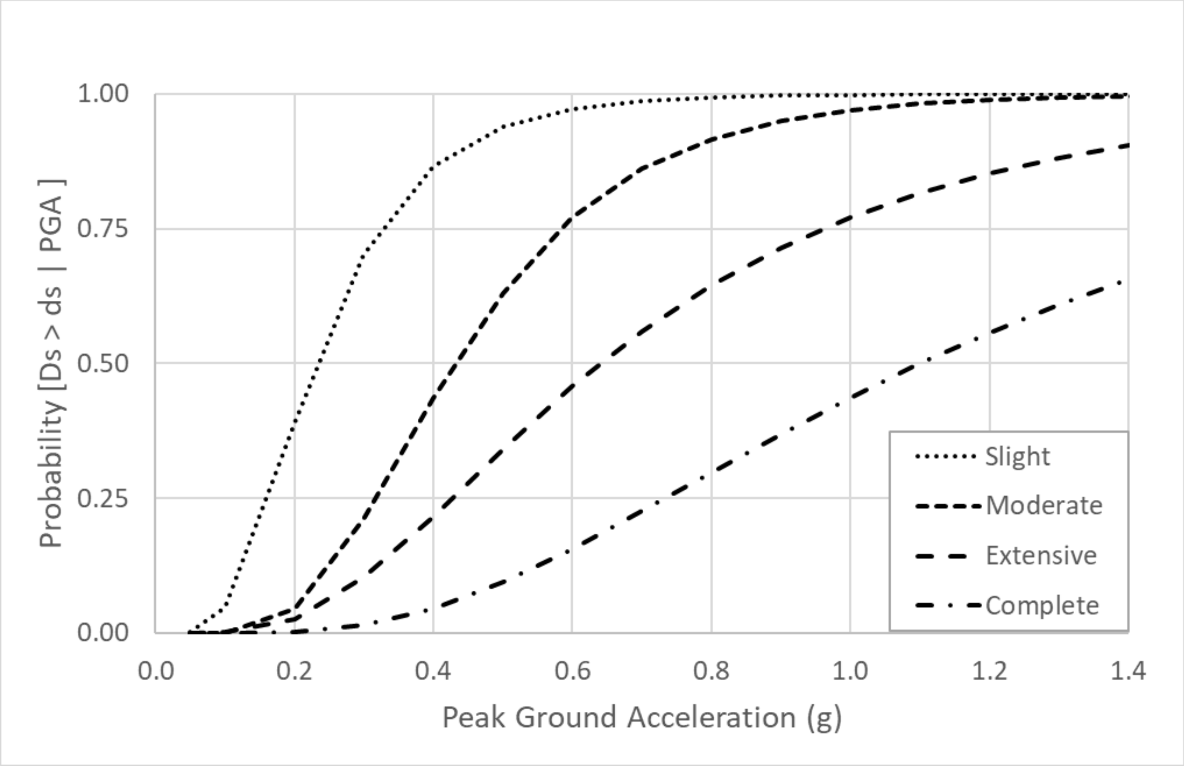


Figure 7-13 Fragility Curves at Various Damage States for Fuel Facility with Anchored Components and Backup Power

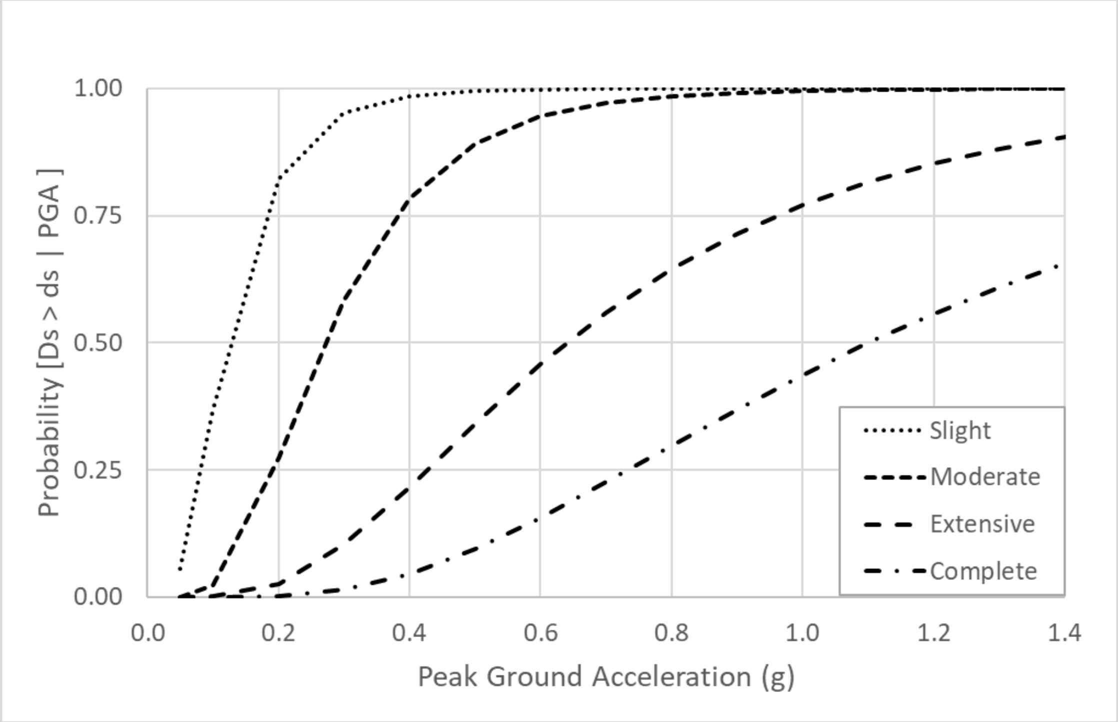


Figure 7-14 Fragility Curves at Various Damage States for Fuel Facility with Anchored Components but no Backup Power

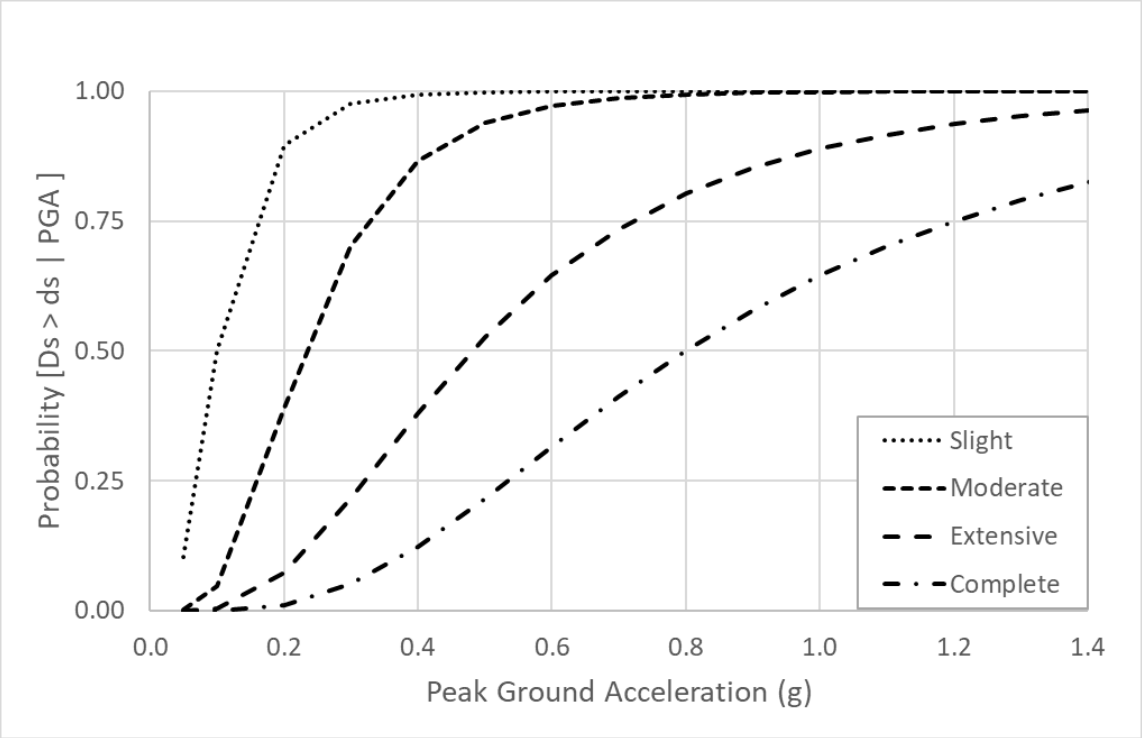


Figure 7-15 Fragility Curves at Various Damage States for Fuel Facility with Unanchored Components and Backup Power

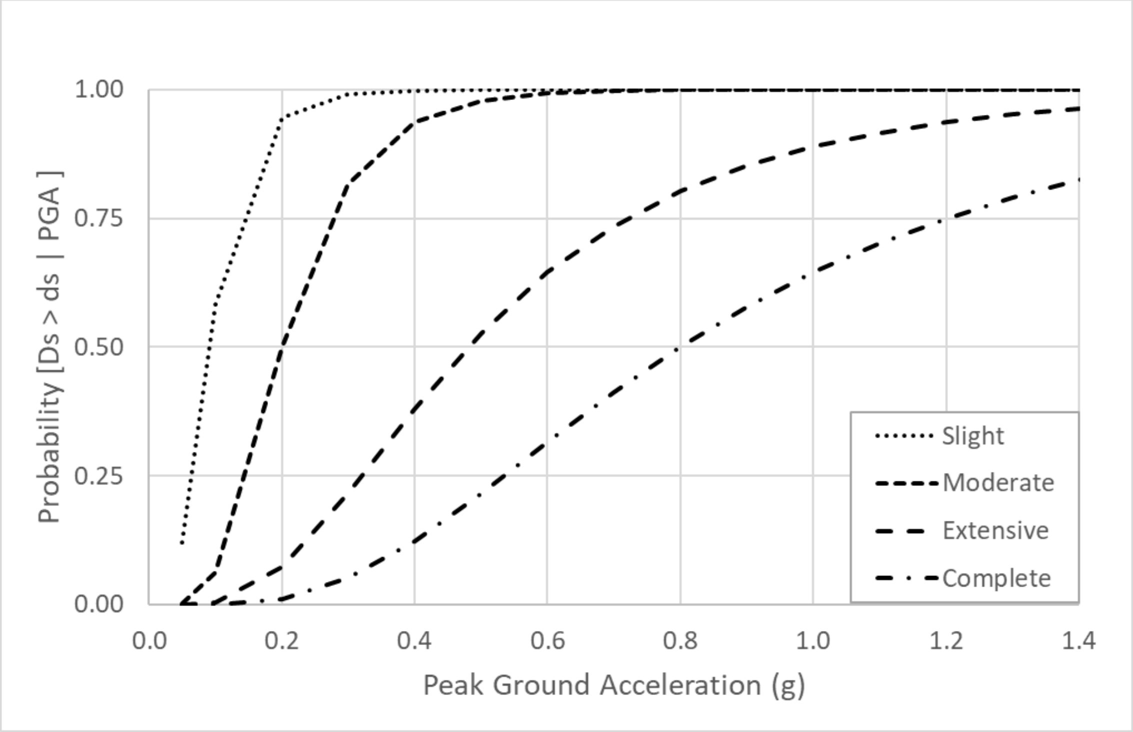


Figure 7-16 Fragility Curves at Various Damage States for Fuel Facility with Unanchored Components but no Backup Power

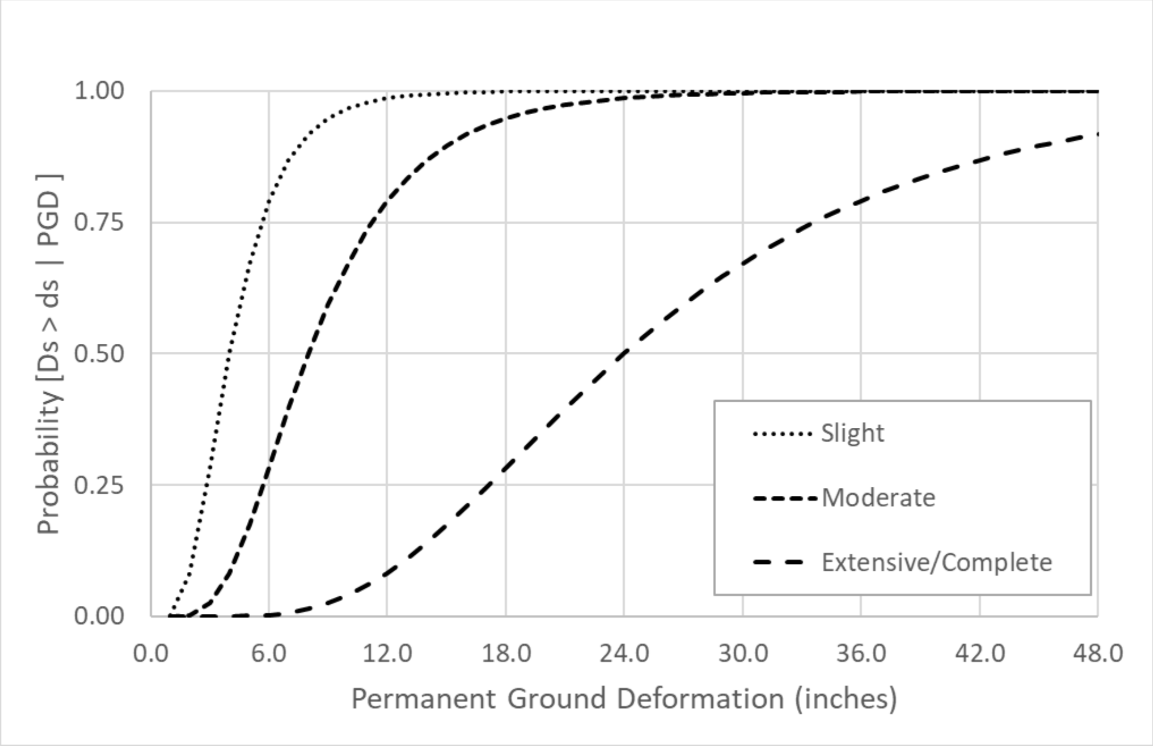


Figure 7-17 Fragility Curves at Various Damage States for Fuel Facility with Buried Tanks Subject to Permanent Ground Deformation

7.2.6.1.2 Damage Functions for Dispatch Facilities

As with fuel facilities, the same generic building type is used in developing the PGA related fragility curves for dispatch facilities in the fault tree logic. The medians and dispersions of the PGA related damage functions for anchored and unanchored dispatch facilities are given in Table 7-14, and plotted in Figure 7-18 through Figure 7-21. Further information on the dispatch facility subcomponent fragilities can be found in Appendix A. Note that the values of Table 7-14 indicate that the damage functions of dispatch facilities are mostly dominated by the building behavior. Damage functions available within Hazus are the functions for unanchored facilities. Users wishing to analyze anchored facilities could revise the existing damage functions through the Hazus menus.

Table 7-14 Peak Ground Acceleration Fragility Functions for Dispatch Facilities

Classification	Damage State	Median (g)	β
Facility with Anchored Components w/Backup Power	Slight	0.15	0.75
	Moderate	0.35	0.65
	Extensive	0.80	0.80
	Complete	1.50	0.80
Facility with Anchored Components w/o Backup Power	Slight	0.12	0.50
	Moderate	0.27	0.45
	Extensive	0.80	0.80
	Complete	1.10	0.80
Facility with Unanchored Components w/ Backup Power	Slight	0.13	0.55
	Moderate	0.28	0.50
	Extensive	0.80	0.80
	Complete	1.50	0.80
Facility with Unanchored Components w/o Backup Power	Slight	0.11	0.45
	Moderate	0.23	0.40
	Extensive	0.80	0.80
	Complete	1.50	0.80

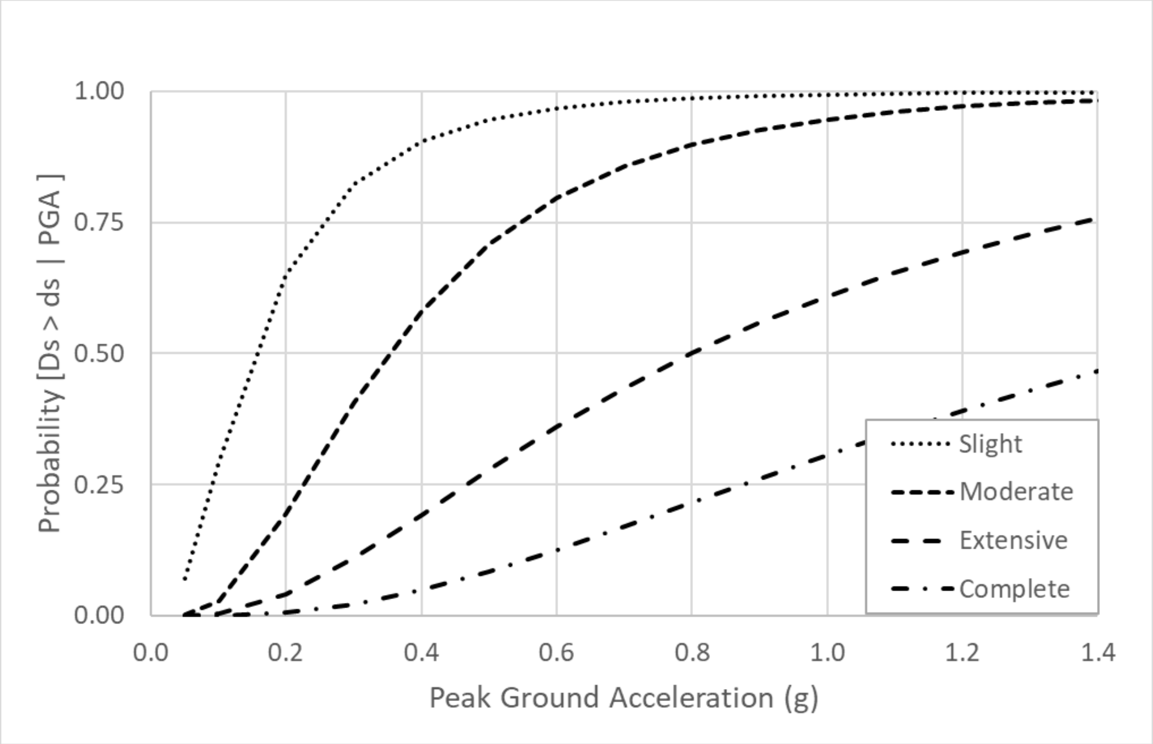


Figure 7-18 Fragility Curves at Various Damage States for Dispatch Facility with Anchored Components and Backup Power

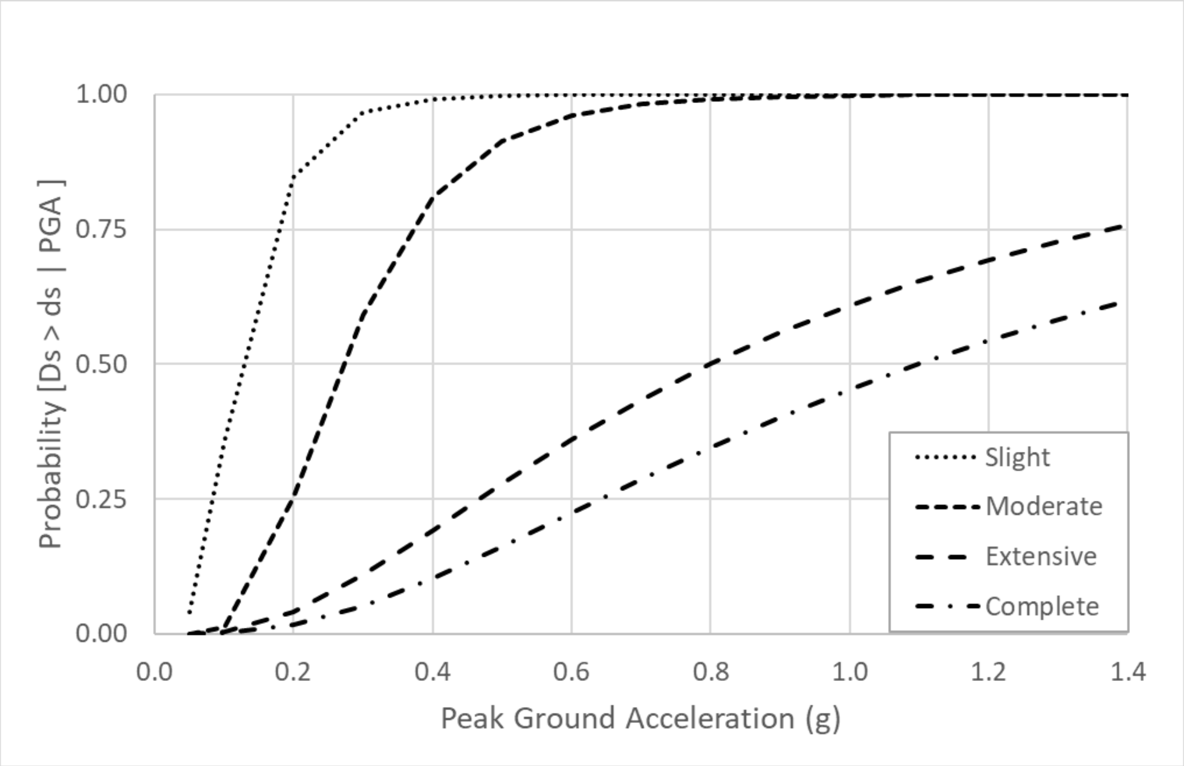


Figure 7-19 Fragility Curves at Various Damage States for Dispatch Facility with Anchored Components but no Backup Power

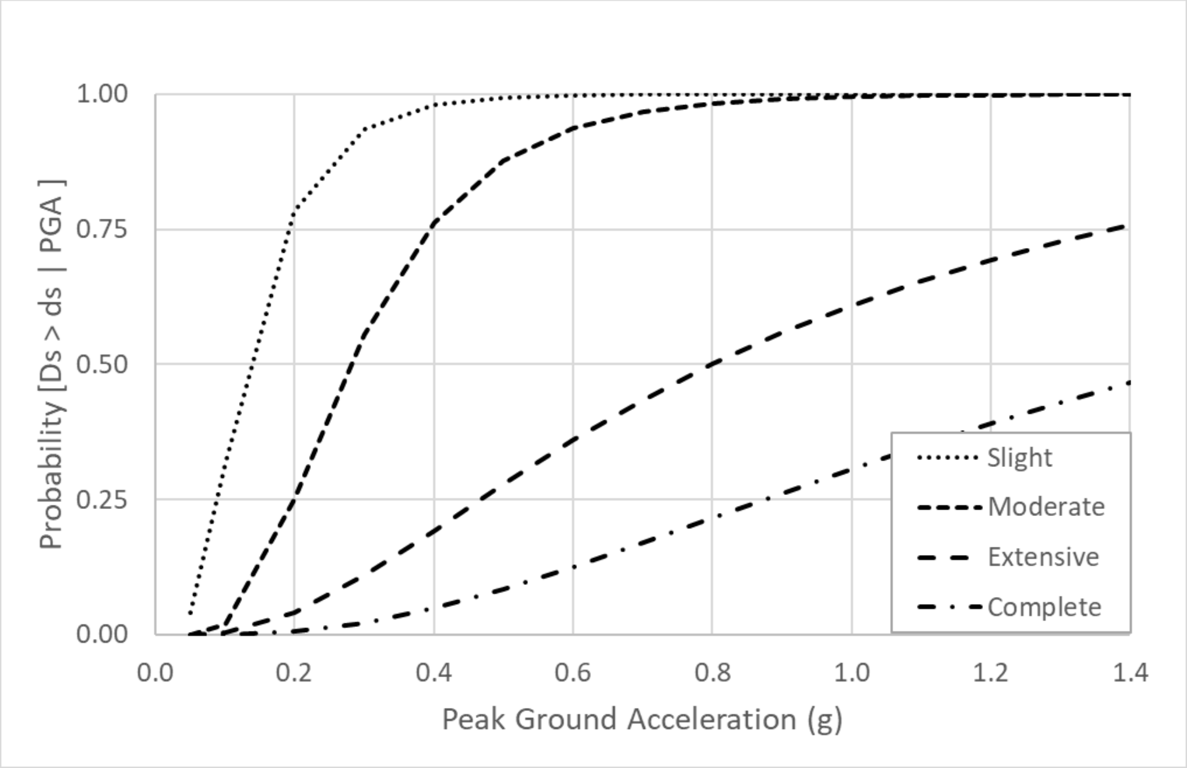


Figure 7-20 Fragility Curves at Various Damage States for Dispatch Facility with Unanchored Components and Backup Power

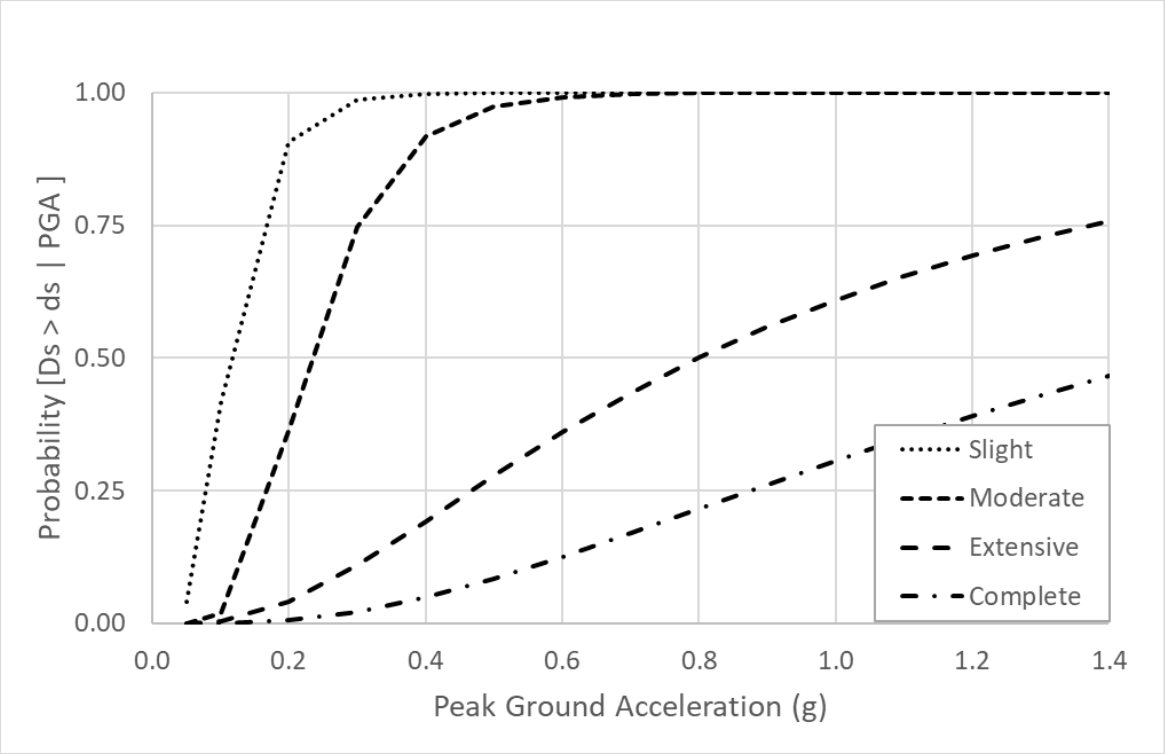


Figure 7-21 Fragility Curves at Various Damage States for Dispatch Facility with Unanchored Components but no Backup Power

7.2.6.2 Multiple Hazards Analysis for Railway System Facilities

In this section, a hypothetical example illustrating the methodology for combining damage state probabilities caused by multiple hazards for nodal facilities is presented.

Assume that due to some earthquake, a railway fuel facility with anchored components and backup power is subject to a PGA level of 0.3g, a lateral spreading displacement of 12 inches, a vertical settlement of 3 inches, and a potential landslide displacement of 15 inches. Assume also that the probability of liquefaction is 0.6, and that the probability of landslide is 0.7.

Due to ground shaking, the following probabilities of exceedance are obtained:

$$\mathrm{P}[\,\mathrm{D_S} \geq \mathrm{Slight} \mid \mathrm{PGA} = 0.3\mathrm{g}\,] = 0.70$$

$$\mathrm{P}[\,\mathrm{D_S} \geq \mathrm{Moderate} \mid \mathrm{PGA} = 0.3\mathrm{g}\,] = 0.21$$

$$\mathrm{P}[\,\mathrm{D_S} \geq \mathrm{Extensive} \mid \mathrm{PGA} = 0.3\mathrm{g}\,] = 0.10$$

$$\mathrm{P}[\,\mathrm{D_S} \geq \mathrm{Complete} \mid \mathrm{PGA} = 0.3\mathrm{g}\,] = 0.02$$

Due to vertical settlement, the following probabilities of exceedance are obtained:

$$\mathrm{P}[\,\mathrm{D_S} \geq \mathrm{Slight} \mid \mathrm{PGD} = 3\ \mathrm{inches}\,] = 0.16$$

$$\mathrm{P}[\,\mathrm{D_S} \geq \mathrm{Moderate} \mid \mathrm{PGD} = 3\ \mathrm{inches}\,] = 0.16$$

$$\mathrm{P}[\,\mathrm{D_S} \geq \mathrm{Extensive} \mid \mathrm{PGD} = 3\ \mathrm{inches}] = 0.16$$

$$\mathrm{P}[\,\mathrm{D_S} \geq \mathrm{Complete} \mid \mathrm{PGD} = 3\ \mathrm{inches}\,] = 20\% * 0.16 = 0.03$$

Due to lateral spreading, the following probabilities of exceedance are obtained:

$$\mathrm{P}[\,\mathrm{D_S} \geq \mathrm{Slight} \mid \mathrm{PGD} = 12\ \mathrm{inches}\,] = 0.09$$

$$\mathrm{P}[\,\mathrm{D_S} \geq \mathrm{Moderate} \mid \mathrm{PGD} = 12\ \mathrm{inches}\,] = 0.09$$

$$\mathrm{P}[\,\mathrm{D_S} \geq \mathrm{Extensive} \mid \mathrm{PGD} = 12\ \mathrm{inches}] = 0.09$$

$$\mathrm{P}[\,\mathrm{D_S} \geq \mathrm{Complete} \mid \mathrm{PGD} = 12\ \mathrm{inches}\,] = 20\% * 0.09 = 0.02$$

Therefore, for liquefaction, vertical settlement controls.

Due to landslide, the following probabilities of exceedance are obtained:

$$\mathrm{P}[\,\mathrm{D_S} \geq \mathrm{Slight} \mid \mathrm{PGD} = 15\ \mathrm{inches}\,] = 0.64$$

$$\mathrm{P}[\,\mathrm{D_S} \geq \mathrm{Moderate} \mid \mathrm{PGD} = 15\ \mathrm{inches}\,] = 0.64$$

$$\mathrm{P}[\,\mathrm{D_S} \geq \mathrm{Extesnive} \mid \mathrm{PGD} = 15\ \mathrm{inches}] = 0.64$$

$$\mathrm{P}[\,\mathrm{D_S} \geq \mathrm{Complete} \mid \mathrm{PGD} = 15\ \mathrm{inches}\,] = 0.64$$

Next, compute the combined probabilities of exceedance (from Complete to Slight):

$$\mathrm{P}[\,\mathrm{D_S} \geq \mathrm{Complete}\ \,] = 0.02 + (0.6 * 0.03) + (0.7 * 0.64) - (0.02 * 0.6 * 0.03) - (0.02 * 0.7 * 0.64) - (0.6 * 0.03 * 0.7 * 0.64) + (0.02 * 0.6 * 0.03 * 0.7 * 0.64) = 0.47$$

$$\mathrm{P[\,D_S \geq Extensive\,] = 0.10 + (0.6 * 0.16) + (0.7 * 0.64) - (0.10 * 0.6 * 0.16) - (0.10 * 0.7 * 0.64) - (0.6 * 0.16 * 0.7 * 0.64) + (0.10 * 0.6 * 0.16 * 0.7 * 0.64) = 0.55}$$

$$\mathrm{P[\,D_S \geq Moderate\,] = 0.21 + (0.6 * 0.16) + (0.7 * 0.64) - (0.21 * 0.6 * 0.16) - (0.21 * 0.7 * 0.64) - (0.6 * 0.16 * 0.7 * 0.64) + (0.21 * 0.6 * 0.16 * 0.7 * 0.64) = 0.61}$$

$$\mathrm{P[\,D_S \geq Slight\,] = 0.70 + (0.6 * 0.16) + (0.7 * 0.64) - (0.70 * 0.6 * 0.16) - (0.16 * 0.7 * 0.64) - (0.6 * 0.16 * 0.7 * 0.64) + (0.70 * 0.6 * 0.16 * 0.7 * 0.64) = 0.85}$$

Therefore, the combined discrete damage states probabilities are:

$$\mathrm{P[\,D_S = None\,] = 1 - 0.85 = 0.15}$$

$$\mathrm{P[\,D_S = Slight\,] = 0.85 - 0.61 = 0.24}$$

$$\mathrm{P[\,D_S = Moderate\,] = 0.61 - 0.55 = 0.06}$$

$$\mathrm{P[\,D_S = Extensive] = 0.55 - 0.47 = 0.08}$$

$$\mathrm{P[\,D_S = Complete] = 0.47}$$

These discrete values will then be used in the evaluation of functionality and economic losses.

7.3 Light Rail Transportation System

This section presents an earthquake loss estimation methodology for a light rail transportation system. Like railway systems, light rail systems consist of railway tracks/roadbeds, bridges, tunnels, maintenance facilities, dispatch facilities, and DC power substations. Therefore, the only difference between rail and light rail systems is in the fuel facilities, which for light rail are DC power substations.

The scope of this section includes development of methods for estimation of earthquake damage to a light rail transportation system given knowledge of the system’s components, the classification of each component (e.g., for dispatch facilities, whether the facility’s equipment is anchored or not), and the hazard (i.e., peak ground acceleration and/or permanent ground deformation).

Damage states describing the level of damage to each light rail system component are defined (i.e., None, Slight, Moderate, Extensive, or Complete). Damage states are related to damage ratio (defined as ratio of repair to replacement cost) for evaluation of direct economic loss. Fragility curves are developed for each type of light rail system component. These curves describe the probability of reaching or exceeding each damage state given the level of ground motion.

Evaluation of component functionality is done in a manner similar to that used for highway and railway components. Component restoration curves are provided for each damage state to evaluate loss of function. Interdependence of components on overall system functionality is not addressed by the methodology. Such considerations require a system (network) analysis that would be performed separately by a light rail system expert as an advanced study.

7.3.1 Input Requirements and Output Information

Required input to estimate damage to light rail systems includes the following items:

- Light Rail Tracks/Roadbeds
    - Geographical location of railway links (polyline segments)
    - Permanent ground deformation (PGD) at railway link
- Light Rail Bridges
    - Bridge classification
    - Geographical location of bridge (longitude and latitude)
    - Spectral acceleration (SA) values and PGD at bridge
- Light Rail Tunnels
    - Tunnel classification
    - Geographical location of tunnels (longitude and latitude)
    - PGA and PGD at tunnel
- Light Rail Facilities (DC substations, maintenance, and dispatch facilities)
    - Facility classification
    - Geographical location of facilities (longitude and latitude)
    - PGA and PGD at facility

Direct damage output for light rail systems includes probability estimates of (1) component functionality, and (2) physical damage, expressed in terms of the component's damage ratio. Note that damage ratios, which are the inputs to direct economic loss methods, are discussed in Section 11.

Component functionality is described by the probability of being in a damage state (immediately following the earthquake) and by the associated fraction or percentage of the component that is expected to be functional after a specified period of time.

7.3.2 Form of Damage Functions

Damage functions or fragility curves for all light rail system components mentioned above are modeled as lognormal functions that give the probability of reaching or exceeding different levels of damage for a given level of ground motion or ground failure. Each fragility curve is characterized by a median value of ground motion (or ground failure) and an associated dispersion factor (lognormal standard deviation). Ground motion is quantified in terms of PGA and spectral acceleration (Sa) and ground failure is quantified in terms of PGD.

- Fragility curves for tracks/roadbeds are the same as for railway tracks/roadbeds, which are similar to those for major roads (see Section 7.1.6.1).
- Fragility curves for bridges are the same as for highway and railway bridges (see Section 7.1.6.2.
- Fragility curves for tunnels are the same as for highway and railway tunnels (see Section 7.1.6.3.
- Fragility curves for maintenance facilities are similar to standard building fragility curves discussed in Section 5.
- Fragility curves for dispatch facilities are the same as for railway dispatch facilities (see Section 7.2.6.1.2).
- Fragility curves for DC power substations are defined in terms of PGA and PGD.

7.3.3 Description of Light Railway System Components

A light rail system consists mainly of six components: tracks/roadbeds, bridges, tunnels, maintenance facilities, dispatch facilities, and DC power substations. The first five are the same as for railway systems and are described in Section 7.2.3. DC Power substations are described below.

DC Power Substations: Light rail systems use electric power and have low voltage DC power substations. The DC power substations consist of electrical equipment, which converts the local electric utility AC power to DC power. Two types of DC power stations are considered. These are: (1) DC power stations with anchored (seismically designed) components and (2) DC power stations with unanchored (which are not seismically designed) components.

7.3.4 Definitions of Damage States

A total of five damage states are defined for light rail system components. These are None, Slight, Moderate, Extensive, and Complete.

Slight Damage

- For tracks/roadbeds, Slight damage is defined similarly to railway tracks (see Section 7.2.4).
- For light rail bridges, Slight damage is defined similarly to highway and railway bridges (see Section 7.1.4).
- For light rail tunnels, Slight damage is defined similarly to highway and railway tunnels (see Section 7.1.4).
- For light rail system facilities:
    - For maintenance facilities, Slight damage is defined similarly to railway stations and maintenance facilities (see Section 7.2.4).
    - For dispatch facilities, Slight damage is defined similarly to railway dispatch facilities (see Section 7.2.4).
    - For DC power substations with anchored or unanchored components, Slight damage is defined by loss of off-site power for a very short period of time, or slight damage to the building.

Moderate Damage

- For tracks/roadbeds, Moderate damage is defined similarly to railway tracks.
- For light rail bridges, Moderate damage is defined similarly to highway and railway bridges.
- For light rail tunnels, Moderate damage is defined similarly to highway and railway tunnels.
- For light rail system facilities:
    - For maintenance facilities, Moderate damage is defined similarly to railway stations and maintenance facilities.
    - For dispatch facilities, Moderate damage is defined similarly to railway dispatch facilities.

    - For DC power substations with anchored or unanchored components, Moderate damage is defined by loss of off-site power for a few days, considerable damage to equipment, or moderate damage to the building.

Extensive Damage

- For tracks/roadbeds, Extensive damage is defined similarly to railway tracks.
- For light rail bridges, Extensive damage is defined similarly to highway and railway bridges.
- For light rail tunnels, Extensive damage is defined similarly to highway and railway tunnels.
- For light rail system facilities:
    - For maintenance facilities, Extensive damage is defined similarly to railway stations and maintenance facilities.
    - For dispatch facilities, Extensive damage is defined similarly to railway dispatch facilities.
    - For DC power substations with anchored or unanchored components, Extensive damage is defined by Extensive building damage; at this level of damage, the performance of the building governs the facility's overall damage state.

Complete Damage

- For tracks/roadbeds, Complete damage is defined similarly to railway tracks.
- For light rail bridges, Complete damage is defined similarly to highway and railway bridges.
- For light rail tunnels, Complete damage is defined similarly to highway and railway tunnels.
- For light rail system facilities:
    - For maintenance facilities, Complete damage is defined similarly to railway stations and maintenance facilities.
    - For dispatch facilities, Complete damage is defined similarly to railway dispatch facilities.
    - For DC power substations with anchored or unanchored components, Complete damage is defined by Complete building damage; at this level of damage, the performance of the building governs the facility's overall damage state.

7.3.5 Component Restoration Curves

The restoration curves for light rail tracks/roadbeds, bridges, tunnels, and facilities are assumed to be the same as those for railway system components (see Section 7.2.5).

7.3.6 Development of Damage Functions

Fragility curves for light rail system components are defined with respect to classification and hazard. Again, except for DC power stations, damage functions of the other light rail system components have been already established in either Section 7.1.6 (highway systems) or Section 7.2.6 (railway systems).

Damage Functions for Dispatch Facilities: Damage functions for light rail system dispatch facilities are defined in terms of PGA and PGD. Note that permanent ground failure related damage functions for these facilities are assumed to be similar to those described for railway system facilities in Section 7.2.6.1.

Damage Functions for Maintenance Facilities: Maintenance facilities for light rail systems are mostly of braced steel frame construction. Damage functions for maintenance facilities are similar to standard building fragility curves discussed in Section 5.

Damage Functions for DC Power Substations: Fragility curves for the two types of DC power substations (with anchored equipment and without anchored equipment) are developed based on the type of damage incurred by the DC power substation subcomponents (building, equipment, and off-site power for interaction effects). Facility fragility functions have been developed from the individual component fragilities through the use of a fault tree analysis, as described in Section 7.2.6.1.1. Further information on the DC power substation facility subcomponent fragilities can be found in Appendix A.

The medians and dispersions of the resulting fragility functions for anchored and unanchored DC power substations are shown in Table 7-15 and plotted in Figure 7-22 and Figure 7-23. Damage functions available within Hazus are the functions for facilities with unanchored components. User's wishing to analyze facilities with anchored components could revise the existing damage functions through the Hazus menus.

Table 7-15 Peak Ground Acceleration Fragility Functions for Light Rail DC Power Substations

Classification	Damage State	Median (g)	β
Substation with Anchored Components	Slight	0.12	0.55
	Moderate	0.27	0.45
	Extensive	0.80	0.80
	Complete	1.50	0.80
Substation with Unanchored Components	Slight	0.11	0.50
	Moderate	0.23	0.40
	Extensive	0.80	0.80
	Complete	1.50	0.80

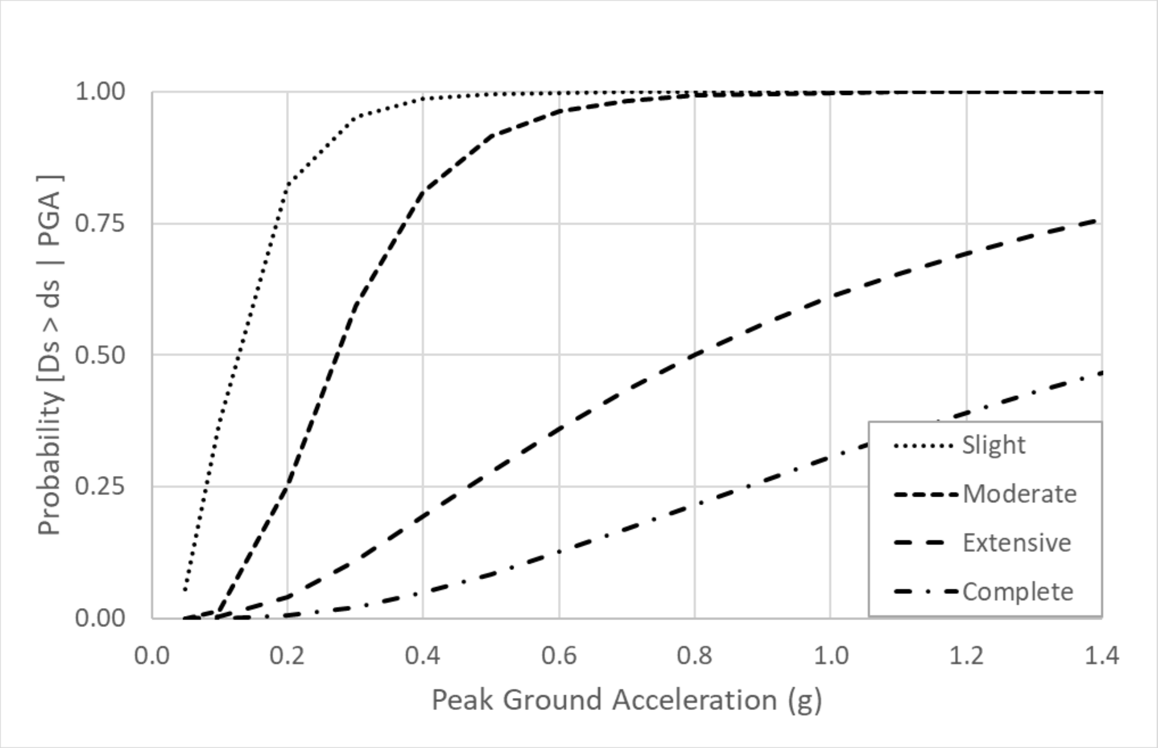


Figure 7-22 Fragility Curves at Various Damage States for DC Power Substations with Anchored Components

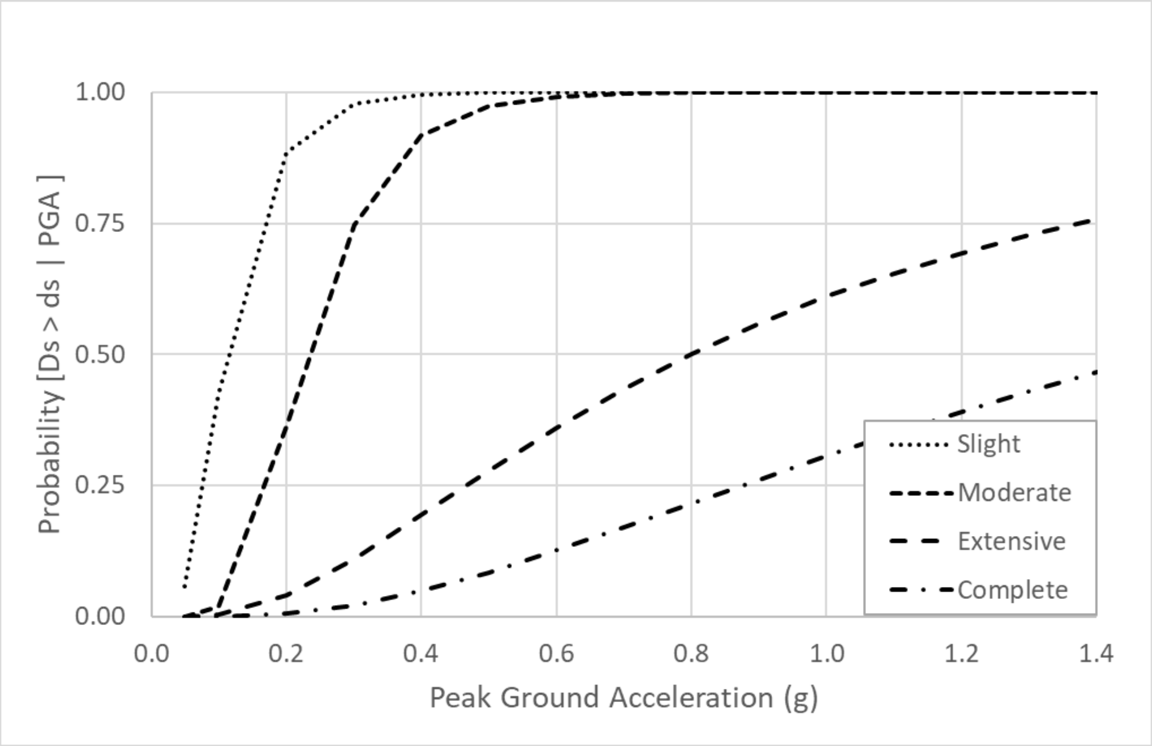


Figure 7-23 Fragility Curves at Various Damage States for DC Power Substations with Unanchored Components

7.4 Bus Transportation System

This section presents an earthquake loss estimation methodology for a bus transportation system. Bus facilities consist of urban stations, maintenance, fuel, and dispatch facilities. The facilities may sustain damage due to ground shaking or ground failure. Major losses can occur if bus maintenance buildings collapse, and operational problems may arise if dispatch facilities are damaged.

The scope of this section includes development of methods for estimation of earthquake damage to a bus transportation system given knowledge of components (i.e., fuel, maintenance, and dispatch facilities with or without backup power), classification (i.e., anchored or unanchored components for fuel facilities), and the hazards (e.g., peak ground acceleration and/or permanent ground deformation).

Damage states describing the level of damage to each of the bus system components are defined (i.e., None, Slight, Moderate, Extensive, or Complete). Damage states are related to damage ratio (defined as ratio of repair to replacement cost) for evaluation of direct economic loss. Fragility curves are developed for each bus system facility type. These curves describe the probability of reaching or exceeding each damage state given the level of ground motion or ground failure.

Evaluation of component functionality is done in a manner similar to that used for highway and railway components. Component restoration curves are provided for each damage state to evaluate loss of function. Restoration curves describe the fraction or percentage of the component that is expected to be open or operational as a function of time following the earthquake. For bus systems, the restoration is dependent upon the extent of damage to the fuel, maintenance, and dispatch facilities.

Interdependence of components on overall system functionality is not addressed by the methodology. Such considerations require a system (network) analysis that would be performed separately by a bus system expert as an advanced study.

7.4.1 Input Requirements and Output Information

Required input to estimate damage to bus systems includes the following items:

- Urban Stations
    - Classification
    - Geographical location of facility (longitude and latitude)
    - Spectral acceleration (SA) values and PGD at station
- Fuel Facilities
    - Classification (i.e., with or without anchored equipment and backup power)
    - Geographical location of facility (longitude and latitude)
    - PGA and PGD at facility
- Maintenance Facilities
    - Classification (i.e., building type)
    - Geographical location of facility (longitude and latitude)
    - SA and PGD at facility
- Dispatch Facilities
    - Classification (i.e., with or without anchored equipment and backup power)

- Geographical location of facility (longitude and latitude)
- PGA and PGD at facility

Direct damage output for bus systems includes probability estimates of (1) component functionality and (2) physical damage, expressed in terms of the component's damage ratio.

Component functionality is described by the probability of being in a damage state (immediately following the earthquake) and by the associated fraction or percentage of the component that is expected to be functional after a specified period of time.

7.4.2 Form of Damage Functions

Damage functions or fragility curves for all four bus system facility types are lognormal functions that give the probability of reaching or exceeding different levels of damage for a given level of ground motion. Each fragility curve is characterized by a median value of ground motion (or failure) and an associated dispersion factor (lognormal standard deviation). Ground motion is quantified in terms of PGA or SA and ground failure is quantified in terms of PGD.

- For urban stations, the fragility curves are defined in terms of SA and PGD.
- For fuel facilities, the fragility curves are defined in terms of PGA and PGD.
- For maintenance facilities, the fragility curves are defined in terms of SA and PGD.
- For dispatch facilities, the fragility curves are defined in terms of PGA and PGD.

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

7.4.3 Description of Bus System Components

A bus system consists mainly of four components: urban stations, fuel facilities, maintenance facilities, and dispatch facilities. This section provides a brief description of each.

Urban Stations: These are mainly building structures.

Bus System Fuel Facilities: Fuel facilities consist of fuel storage tanks, buildings, pump equipment and buried pipe, and sometimes backup power. The fuel facility functionality is determined with a fault tree analysis considering redundancies and sub-component behavior (see Section 7.2.6.1.1). The same sub-classes assumed for railway fuel facilities are assumed here.

Bus System Maintenance Facilities: Maintenance facilities for bus systems are mostly of braced steel frames Construction. The same classes assumed for railway maintenance facilities are assumed here.

B*us System Dispatch Facilities*: The same classes assumed for railway dispatch facilities are assumed here.

7.4.4 Definitions of Damage States

A total of five damage states are defined for bus system components. These are None, Slight, Moderate, Extensive, and Complete. For all damage states, bus facility damage is defined similarly to the equivalent railway facility type (see Section 7.2.4), as follows:

- For urban bus stations, all damage states are defined similarly to those for railway urban stations.

- For bus fuel facilities, all damage states are defined similarly to those for railway fuel facilities.
- For bus maintenance facilities, all damage states are defined similarly to those for railway maintenance facilities.
- For bus dispatch facilities, all damage states are defined similarly to those for railway dispatch facilities.

7.4.5 Component Restoration Curves

Restoration Curves have been developed based on a best fit to ATC-13 (ATC, 1985) damage data for the social functions SF 26a through SF 26d, consistent with damage states defined in Section 7.4.4. Normally distributed functions are used to approximate these restoration curves, as was done for highway and railway systems. The restoration curves for bus transportation systems are then same as those of railway transportation systems. Means and dispersions of these restoration functions are given in Table 7-14. Discretized restoration functions are shown in Table 7-15, where the percentage restoration is shown at discrete times. Although not directly used in Hazus, the discretized restoration functions are presented here as guidance.

7.4.6 Development of Damage Functions

Fragility curves for bus system components are defined with respect to facility classification and hazard parameter.

Damage Functions for Bus System Urban Stations: Urban stations are classified based on the building structural type. Damage functions for urban stations are similar to standard building fragility curves discussed in Section 5.

Damage Functions for Bus System Fuel Facilities: Fuel facilities are classified based on two criteria: (1) whether the sub-components comprising the fuel facilities are anchored or unanchored and (2) whether backup power exists in the facility. Damage functions for bus system fuel facilities are the same as those for the railway transportation system (see Section 7.2.6.1.1).

Damage Functions for Bus System Maintenance Facilities: Damage functions for bus maintenance facilities are similar to standard building fragility curves discussed in Section 5.

Damage Functions for Bus System Dispatch Facility: The PGA and PGD median values for the damage states of dispatch facilities are the same as those of railway dispatch facilities given in Section 7.2.6.1.2.

7.5 Port Transportation System

This section presents an earthquake loss estimation methodology for a port transportation system. Port facilities consist of waterfront structures (e.g., wharves, piers, and seawalls), cranes and cargo handling equipment, fuel facilities, and warehouses. In many cases, these facilities were constructed prior to widespread use of engineered fills; consequently, the wharf, pier, and seawall structures are prone to damage due to soil failures such as liquefaction. Other components may be damaged due to ground shaking as well as ground failure.

The scope of this section includes developing methods for estimating earthquake damage to a port transportation system given knowledge of components (i.e., waterfront structures, cranes and cargo handling equipment, fuel facilities, and warehouses), classification (i.e., for fuel facilities, anchored or unanchored components, with or without backup power), and the hazards (i.e,. peak ground acceleration and/or permanent ground deformation).

Damage states describing the level of damage to each of the port system components are defined (i.e., None, Slight, Moderate, Extensive, or Complete). Damage states are related to damage ratio (defined as ratio of repair to replacement cost) for evaluation of direct economic loss. Fragility curves are developed for each class of port system component. These curves describe the probability of reaching or exceeding a certain damage state given the level of ground motion. Based on these fragility curves, a method for assessing functionality of each of the four port system components is presented.

Evaluation of component functionality is done in a manner similar to that used for highway and railway components. Component restoration curves are provided for each damage state to evaluate loss of function. Restoration curves describe the fraction or percentage of the component that is expected to be open or operational as a function of time following the earthquake. For ports, restoration is dependent upon the extent of damage to the waterfront structures, cranes/cargo handling equipment, fuel facilities, and warehouses. From the standpoint of functionality of the port, the user should consider the restoration of only the waterfront structures and cranes since the fuel facilities and warehouses are not as critical to the functionality of the port.

Interdependence of components on overall system functionality is not addressed by the methodology. Such considerations require a system (network) analysis that would be performed separately by a port system expert as an advanced study.

7.5.1 Input Requirements and Output Information

Required input to estimate damage to port systems includes the following items:

- Waterfront Structures
  - Classification
  - Geographic location of structure (longitude and latitude)
  - PGA and PGD
- Cranes/Cargo Handling Equipment
  - Classification (i.e., stationary or rail mounted)
  - Geographic location of equipment (longitude and latitude)
  - PGA and PGD
- Fuel Facilities
  - Classification (i.e., with or without anchored equipment and backup power)
  - Geographical location of facility (longitude and latitude)
  - PGA and PGD
- Warehouses
  - Classification (i.e., building type)
  - Geographical location of warehouse (longitude and latitude)
  - PGA and PGD

Direct damage output for port systems includes probability estimates of (1) component functionality and (2) physical damage, expressed in terms of the component’s damage ratio. Damage ratios are used as inputs to direct economic loss methods, as discussed in Section 11.

Component functionality is described by the probability of being in a damage state (immediately following the earthquake) and by the associated fraction or percentage of the component that is expected to be functional after a specified period of time.

7.5.2 Form of Damage Functions

Damage functions or fragility curves for all four port system components are lognormally distributed functions that give the probability of reaching or exceeding different levels of damage for a given level of ground motion or ground failure. Each fragility curve is characterized by a median value of ground motion (or failure) and an associated dispersion factor (lognormal standard deviation). Ground motion is quantified in terms of PGA and ground failure is quantified in terms of PGD.

- For waterfront structures, the fragility curves are defined in terms of PGA and PGD.
- For cranes/cargo handling equipment, the fragility curves are defined in terms of PGA and PGD.
- For fuel facilities, the fragility curves are defined in terms of PGA and PGD.
- For warehouses, the fragility curves are defined in terms of PGA and PGD.

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

7.5.3 Description of Port Components

A port system consists of four components: waterfront structures, cranes/cargo handling equipment, fuel facilities, and warehouses. This section provides a brief description of each.

- *Waterfront Structures*: Waterfront structures include wharves (port embankments), seawalls (protective walls from erosion), and piers (break-water structures which form harbors). Waterfront structures typically are supported by wood, steel, or concrete piles. Many also have batter piles to resist lateral loads from wave action and impact of vessels. Seawalls are caisson walls retaining earth fill material.
- *Cranes and Cargo Handling Equipment*: These are large equipment items used to load and unload freight from vessels. These can be stationary or mounted on rails.
- *Port Fuel Facilities*: The fuel facility consists mainly of fuel storage tanks, buildings, pump equipment, piping, and sometimes backup power. These facilities are as assumed to be equivalent to those for railway systems presented in Section 7.2.3. The functionality of fuel systems is determined with a fault tree analysis, which considers redundancies and sub-component behavior.
- *Warehouses*: Warehouses are large buildings usually constructed of structural steel. In some cases, warehouses may be several hundred feet from the shoreline, while in other instances; they may be located on the wharf itself.

7.5.4 Definition of Damage States

A total of five damage states are defined for port system components. These are None, Slight, Moderate, Extensive, and Complete.

Slight Damage

- For waterfront structures, Slight damage is defined by minor ground settlement resulting in a few piles (for piers/seawalls) getting broken and damaged. Cracks are formed on the surface of the wharf. Repair may be needed.
- For cranes/cargo handling equipment, Slight damage is defined by slight damage to structural members with no loss of function for the stationary equipment, while for the unanchored or rail mounted equipment, Slight damage is defined as minor derailment or misalignment without any major structural damage to the rail mount. Minor repair and adjustments may be required before the crane becomes operable.
- For waterfront fuel facilities, Slight damage is defined the same as for railway fuel facilities (see Section 7.2.4).
- For warehouses, whose performance is governed by the performance of the buildings themselves, Slight damage is defined as Slight damage to the warehouse building.

Moderate Damage

- For waterfront structures, Moderate damage is defined as considerable ground settlement with several piles (for piers/seawalls) broken and damaged.
- For cranes/cargo handling equipment, Moderate damage is defined as derailment due to differential displacement of parallel track. Rail repair and some repair to structural members is required.
- For fuel facilities, Moderate damage is defined the same as for railway fuel facilities.
- For warehouses, Moderate damage is defined as Moderate damage to the warehouse building.

Extensive Damage

- For waterfront structures, Extensive damage is defined by failure of many piles, extensive sliding of piers, and significant ground settlement causing extensive cracking of pavements.
- For cranes/cargo handling equipment, Extensive damage is defined by considerable damage to equipment. Toppled or totally derailed cranes are likely to occur. Replacement of structural members is required.
- For fuel facilities, Extensive damage is defined the same as for railway fuel facilities.
- For warehouses, Extensive damage is defined as Extensive damage to the warehouse building.

Complete Damage

- For waterfront structures, Complete damage is defined as failure of most piles due to significant ground settlement. Extensive damage is widespread at the port facility.
- For cranes/cargo handling equipment, Complete damage is the same as Extensive damage.
- For fuel facilities, Complete damage is the same as for railway fuel facilities.
- For warehouses, Complete damage is defined as Complete damage to the warehouse building.

7.5.5 Component Restoration Curves

Restoration Curves are developed based on a best fit to ATC-13 (ATC, 1985) damage data for social functions SF 28.a and SF 29.b, consistent with damage states defined in the previous section. Normally distributed functions are used to approximate these restoration curves, as was done for highway and railway systems. Means and dispersions of these restoration functions are given in Table 7-16. These restoration functions are shown in Figure 7-24 and Figure 7-25. Figure 7 24 represents restoration curves for waterfront structures, while Figure 7-25 shows restorations curve for cranes and cargo handling equipment.

The discretized restoration functions are given in Table 7-17, where the percentage restoration is shown at some specified time intervals. Although not directly used in Hazus, the discretized restoration functions are presented here as guidance.

Table 7-16 Restoration Functions for Port System Components (All Normal Distributions)

Classification	Damage State	Mean (Days)	σ days)
Buildings, Waterfront Structures	Slight	0.6	0.2
	Moderate	3.5	3.5
	Extensive	22	22
	Complete	85	73
Cranes/Cargo Handling Equipment	Slight	0.4	0.35
	Moderate	6	6
	Extensive	30	30
	Complete	75	55

Table 7-17 Discretized Restoration Functions for Port System Components

Classification	Damage State	Functional Percentage				
		1 day	3 days	7 days	30 days	90 days
Buildings, Waterfront Structures	Slight	96	100	100	100	100
	Moderate	24	43	84	100	100
	Extensive	17	19	63	63	100
	Complete	12	13	22	22	53
Cranes/Cargo Handling Equipment	Slight	96	100	100	100	100
	Moderate	20	31	57	100	100
	Extensive	17	18	22	50	100
	Complete	9	10	11	21	62

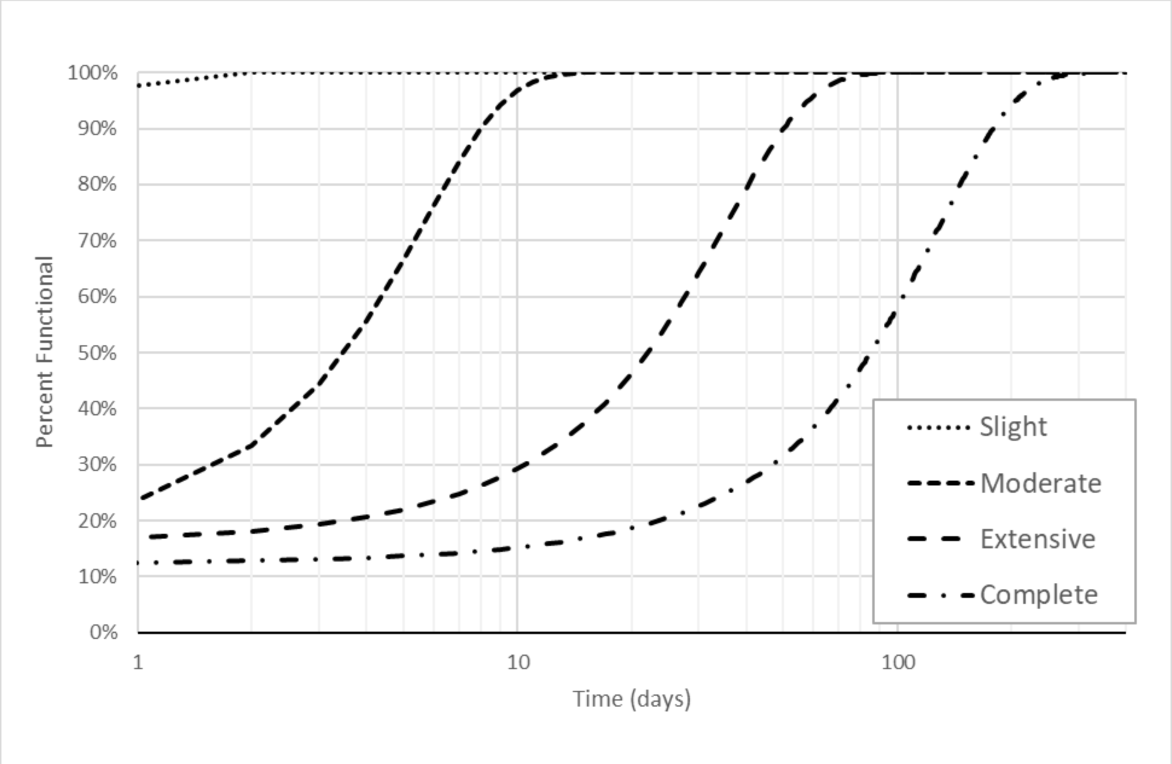


Figure 7-24 Restoration Curves for Waterfront Structures

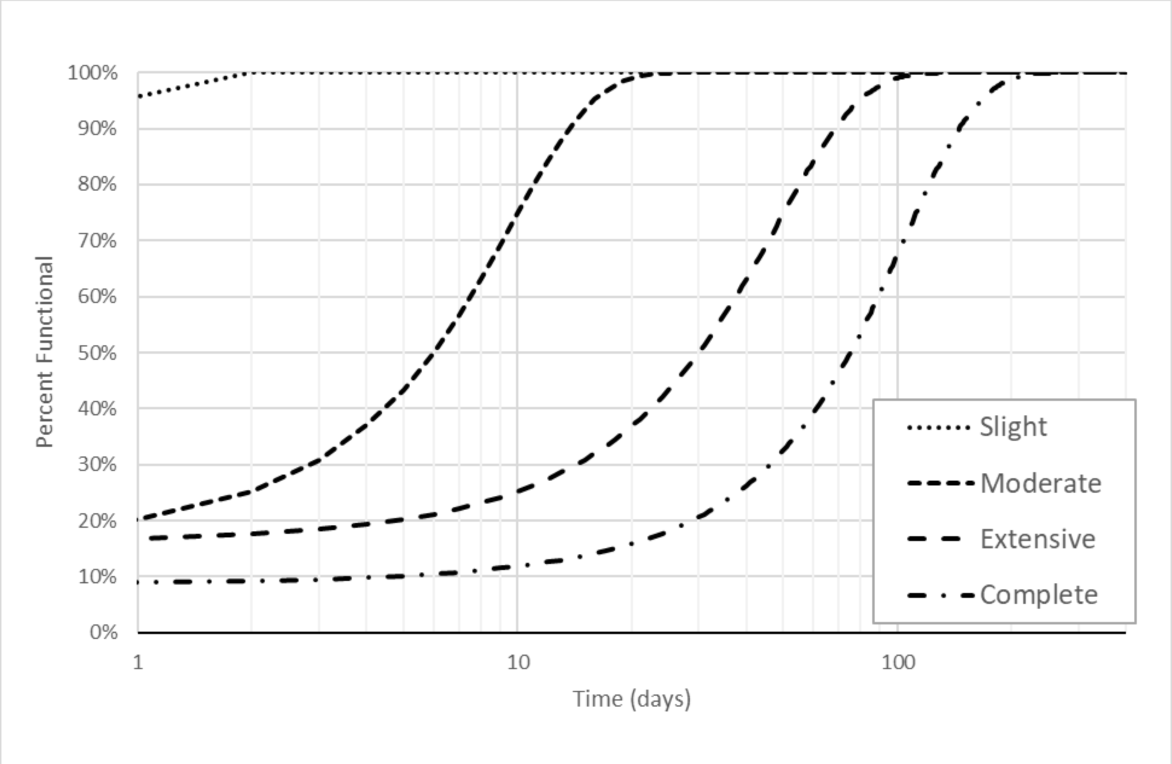


Figure 7-25 Restoration Curves for Cranes/Cargo Handling Equipment

7.5.6 Development of Damage Functions

Damage functions for port system facilities are defined in terms of PGA and PGD. Note that unless it is specified otherwise, permanent ground failure related damage functions for these facilities are assumed to be similar to those described for railroad system facilities in Section 7.2.6. An example of how to combine PGD and PGA damage state probability distributions is presented in Section 7.2.6.2.

7.5.6.1 Damage functions for Waterfront Structures

Damage functions for waterfront structures were established based on damageability of subcomponents, namely, piers, seawalls, and wharves. Fault tree logic and the lognormal best fitting technique were used in developing these fragility curves. The fault tree is implicitly described in the description of the damage state. Further information on the waterfront structure subcomponent fragilities can be found in the Appendix A. The resulting fragility functions are shown in Figure 7-26 and their medians and dispersions are given in Table 7-18.

Table 7-18 Permanent Ground Deformation Fragility Function for Waterfront Structures

Components	Damage State	Median (in)	Beta
Waterfront Structures (PWS)	Slight	5	0.50
	Moderate	12	0.50
	Extensive	17	0.50
	Complete	43	0.50

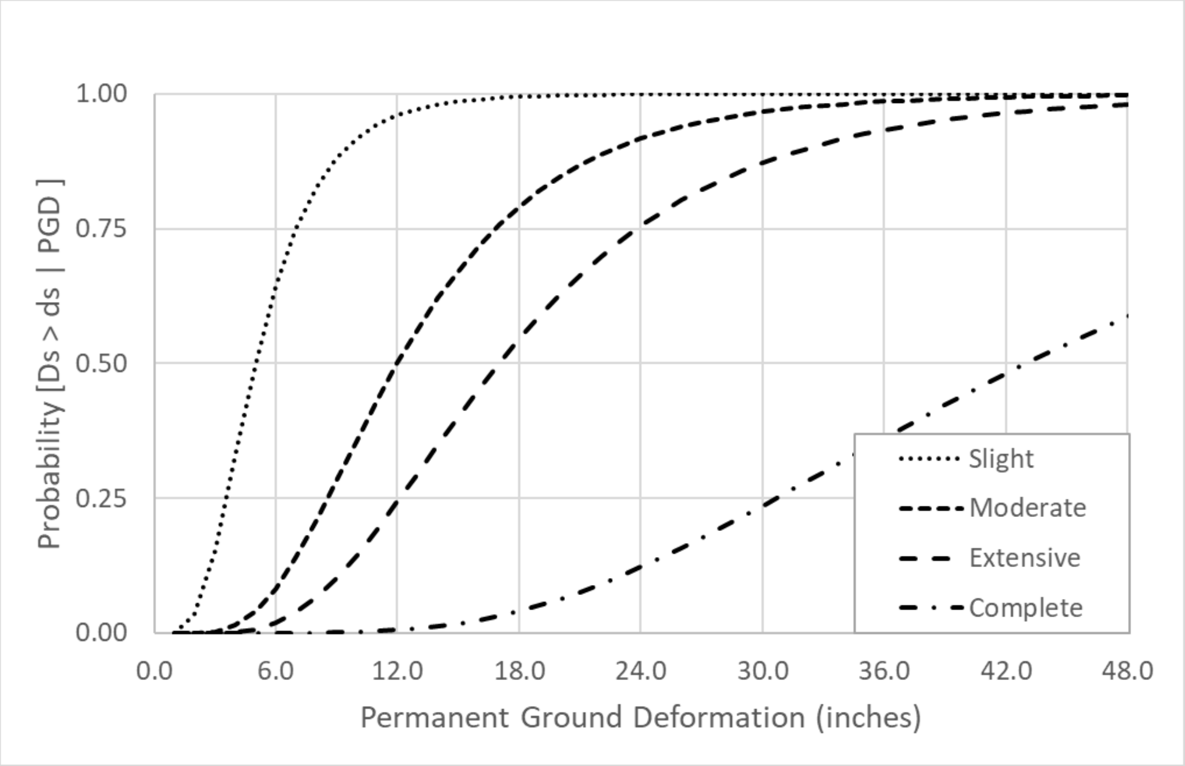


Figure 7-26 Fragility Curves for Port Waterfront Structures

7.5.6.2 Damage Functions for Cranes and Cargo Handling Equipment

For cranes, a distinction is made between stationary and rail-mounted cranes. The medians and dispersions of fragility functions are presented in Table 7-19 and Table 7-20, for ground shaking and ground failure, while the fragility curves are shown in Figure 7-27 through Figure 7-30. Damage functions available within Hazus are the functions for unanchored equipment. User's wishing to analyze anchored equipment could revise the existing damage functions through the Hazus menus.

Table 7-19 Peak Ground Acceleration Fragility Functions for Cranes/Cargo Handling Equipment

Classification	Damage State	Median (g)	β
Anchored/ Stationary (PEQ1)	Slight	0.3	0.6
	Moderate	0.5	0.6
	Extensive/Complete	1.0	0.7
Unanchored/Rail-mounted (PEQ2)	Slight	0.15	0.6
	Moderate	0.35	0.6
	Extensive/Complete	0.8	0.7

Table 7-20 Permanent Ground Deformation Fragility Functions for Cranes/Cargo Handling Equipment

Classification	Damage State	Median (in)	β
Anchored/ Stationary (PEQ1)	Slight	3	0.6
	Moderate	6	0.7
	Extensive/ Complete	12.0	0.7
Unanchored/Rail mounted (PEQ2)	Slight	2	0.6
	Moderate	4.0	0.6
	Extensive/ Complete	10	0.7

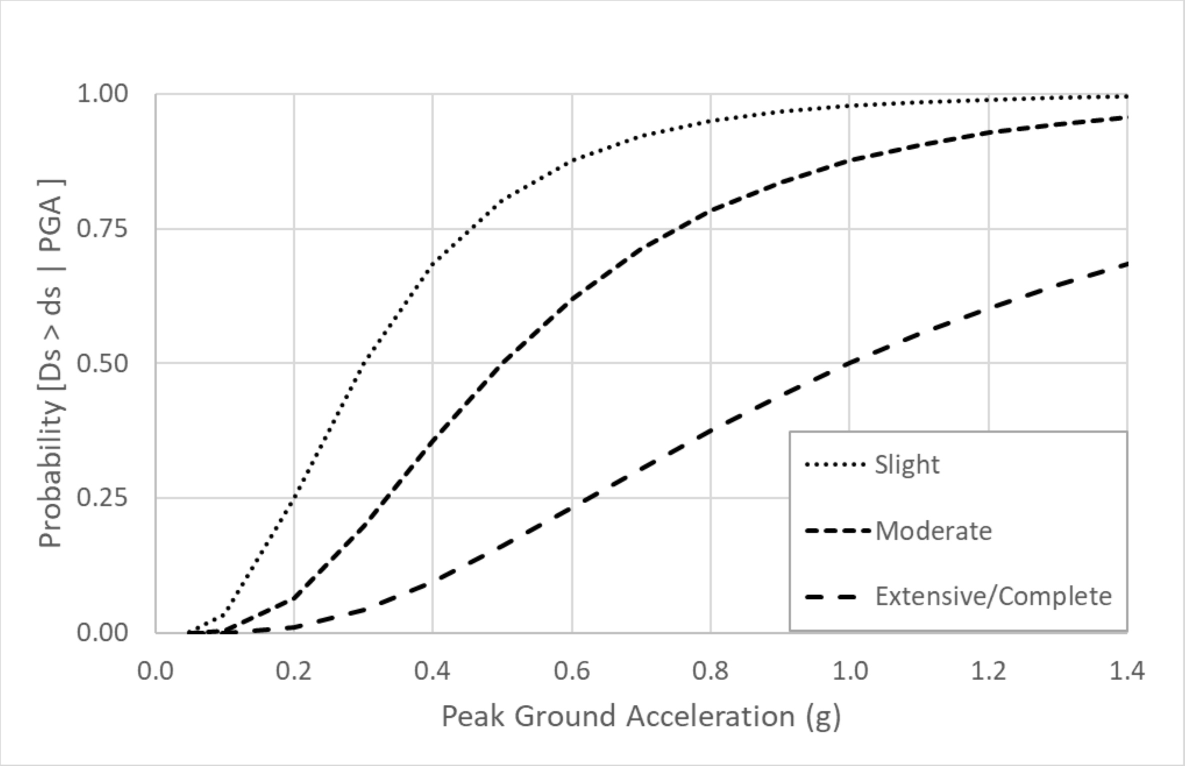


Figure 7-27 Fragility Curves for Stationary Cranes/Cargo Handling Equipment Subject to Ground Shaking

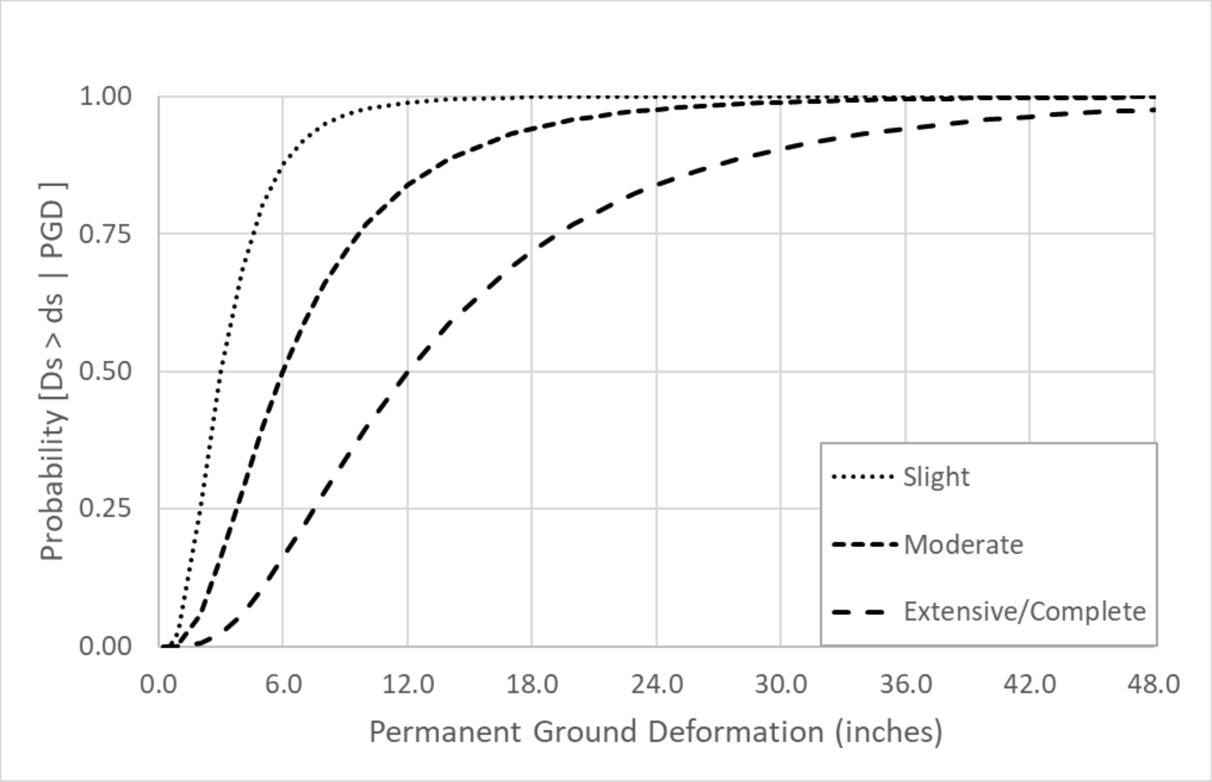


Figure 7-28 Fragility Curves for Stationary Cranes/Cargo Handling Equipment Subject to Permanent Ground Deformation

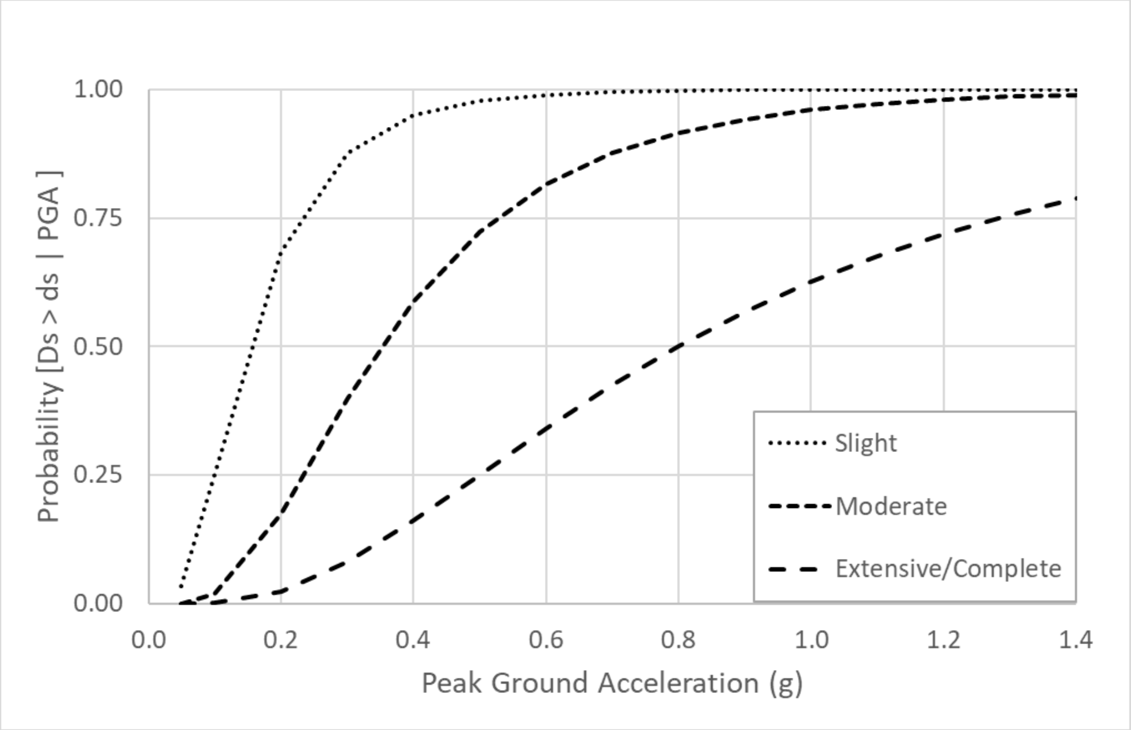


Figure 7-29 Fragility Curves for Rail-Mounted Cranes/Cargo Handling Equipment Subject to Ground Shaking

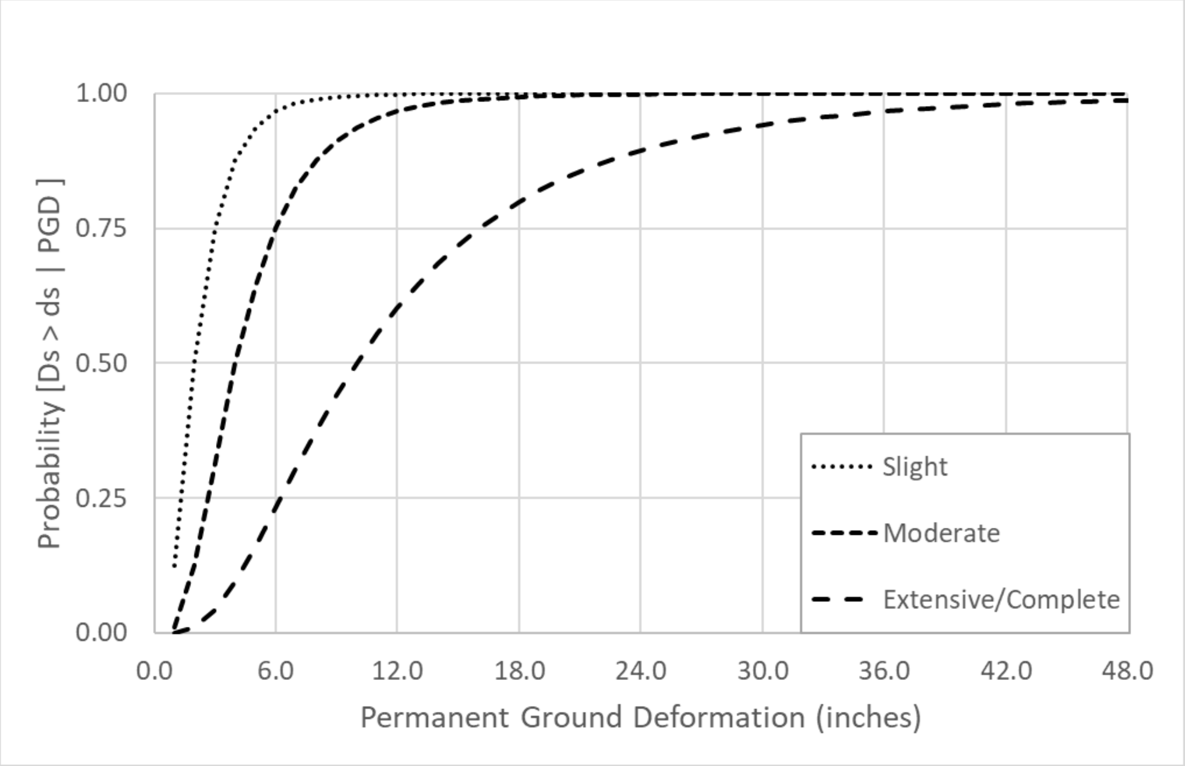


Figure 7-30 Fragility Curves for Rail Mounted Cranes/Cargo Handling Equipment Subject to Permanent Ground Deformation

7.5.6.3 Damage Functions for Port System Fuel Facilities

Damage functions for fuel facilities are to the same as those developed for railway fuel facilities in Section 7.2.6.1.1.

7.5.6.4 Damage Functions for Warehouses

Damage functions for port warehouses are similar to standard building fragility curves discussed in Section 5.

7.6 Ferry Transportation System

This section presents a loss estimation methodology for a ferry transportation system. Ferry systems consist of waterfront structures (e.g., wharves, piers, and seawalls), fuel, maintenance, and dispatch facilities, and passenger terminals.

The waterfront structures are located at the points of embarkation or disembarkation, and they are similar to, although not as extensive as those of the port transportation system. In some cases, the ferry system may be located within the boundary of the port transportation system. The points of embarkation or disembarkation are located some distance apart from one another, usually on opposite shorelines.

Fuel and maintenance facilities are usually located at one of these two points. The size of the fuel facility is smaller than that of the port facility. In many cases, the dispatch facility is located in the maintenance facility or one of the passenger terminals.

The scope of this section includes development of methods for estimation of earthquake damage to a ferry transportation system given knowledge of components (i.e., waterfront structures, fuel, maintenance, and dispatch facilities, and passenger terminals), classification (i.e., for fuel facilities, anchored or unanchored components, with or without back-up power), and the hazards (i.e., peak ground acceleration and/or permanent ground deformation).

Damage states describing the level of damage to each of the ferry system components are defined (i.e., None, Slight, Moderate, Extensive, or Complete). Damage states are related to damage ratio (defined as ratio of repair to replacement cost) for evaluation of direct economic loss, as described in Section 11. Fragility curves are developed for each class of the ferry system components. These curves describe the probability of reaching or exceeding each damage state given the level of ground motion or ground failure.

Evaluation of component functionality is done in a manner similar to that used for highway and railway components. Component restoration curves are provided for each damage state to evaluate loss of function. Restoration curves describe the fraction or percentage of the component that is expected to be open or operational as a function of time following the earthquake. For ferries, the restoration is dependent upon the extent of damage to the waterfront structures, fuel, maintenance and dispatch facilities, and passenger terminals.

Interdependence of components on overall system functionality is not addressed by the methodology. Such considerations require a system (network) analysis that would be performed separately by a transportation system expert as an advanced study.

7.6.1 Input Requirements and Output Information

Required input to estimate damage to ferry system includes the following items:

- Ferry Waterfront Structures
    - Geographic locations of structures (longitude and latitude)
    - PGA and PGD
- Ferry Fuel Facilities
    - Classification (i.e., with or without anchored equipment and backup power)
    - Geographical location of facility (longitude and latitude)
    - PGA and PGD
- Ferry Maintenance Facilities
    - Classification (i.e., building type)
    - Geographical location of facility (longitude and latitude)
    - SA and PGD
- Ferry Dispatch Facilities
    - Classification (i.e., with or without anchored equipment and backup power)
    - Geographical location of facility (longitude and latitude)
    - PGA and PGD
- Ferry Terminal Buildings
    - Classification (i.e., building type)
    - Geographical location of building (longitude and latitude)
    - SA and PGD

Direct damage output for ferry systems includes probability estimates of (1) component functionality and (2) physical damage, expressed in terms of the component's damage ratio. Damage ratios are used as inputs to direct economic loss methods.

7.6.2 Form of Damage Functions

Damage functions or fragility curves for all five ferry system components mentioned above are lognormal functions that give the probability of reaching or exceeding different levels of damage for a given level of ground motion. Each fragility curve is characterized by a median value of ground motion (or failure) and an associated dispersion factor (lognormal standard deviation). Ground motion is quantified in terms of PGA or SA and ground failure is quantified in terms of PGD.

- For waterfront structures, the fragility curves are defined in terms of PGA and PGD.
- For fuel facilities and dispatch facilities, the fragility curves are defined in terms of PGA and PGD.
- For maintenance and terminal buildings, the fragility curves are defined in terms of SA and PGD.

Definitions of various damage states and the methodology used in deriving fragility curves for ferry system components are presented in the following sections.

7.6.3 Description of Ferry System Components

A ferry system consists of the five components mentioned above: waterfront structures, fuel facilities, maintenance facilities, dispatch facilities, and passenger terminals. This section provides a brief description of each.

- *Waterfront Structures*: These are the same as those described for port systems in Section 7.5.3.
- *Fuel Facilities*: These facilities are similar to those for port systems mentioned in Section 7.5.3.
- *Maintenance Facilities*: These are often steel braced frame structures, but other building types are possible.
- *Dispatch Facilities*: These are similar to those defined for railway systems in Section 7.2.3.
- *Passenger Terminals*: These are often moment resisting steel frames, but other building types are possible.

7.6.4 Definitions of Damage States

A total of five damage states are defined for ferry system components. These are None, Slight, Moderate, Extensive, and Complete.

Slight Damage

- For waterfront structures, Slight damage is the same as that for waterfront structures in the port module (see Section 7.5.4).
- For fuel facilities, Slight damage is the same as that for fuel facilities in the railway module (see Section 7.2.4).
- For maintenance facilities, whose performance is governed by the performance of the buildings themselves, Slight damage is defined as Slight damage to the building.
- For dispatch facilities, Slight damage is the same as that for dispatch facilities in the railway module (see Section 7.2.4).
- For passenger terminals, Slight damage is defined as Slight damage to the building.

Moderate Damage

- For waterfront structures, Moderate damage is the same as that for waterfront structures in the port module.
- For fuel facilities, Moderate damage is the same as that for fuel facilities in the railway module.
- For maintenance facilities, Moderate damage is defined as Moderate damage to the building.
- For dispatch facilities, Moderate damage is the same as that for dispatch facilities in the railway module.
- For passenger terminals, Moderate damage is defined as Moderate damage to the building.

Extensive Damage

- For waterfront structures, Extensive damage is the same as that for waterfront structures in the port module.
- For fuel facilities, Extensive damage is the same as that for fuel facilities in the railway module.

- For maintenance facilities, Extensive damage is defined as Extensive damage to the building.
- For dispatch facilities, Extensive damage is the same as that for dispatch facilities in the railway module.
- For passenger terminals, Extensive damage is defined as Extensive damage to the building.

Complete Damage

- For waterfront structures, Complete damage is the same as that for waterfront structures in the port module.
- For fuel facilities, Complete damage is the same as that for fuel facilities in the railway module.
- For maintenance facilities, Complete damage is defined as Complete damage to the building.
- For dispatch facilities, Complete damage is the same as that for dispatch facilities in the railway module.
- For passenger terminals, Complete damage is defined as Complete damage to the building.

7.6.5 Component Restoration Curves

Ferry systems are made of components that are similar to either those in port systems (i.e., waterfront structures), or those in railway systems (i.e., fuel facilities, dispatch facilities, maintenance facilities, and passenger terminals). Therefore, restoration curves for ferry system components can be found in Sections 7.2.5 and 7.5.5.

7.6.6 Development of Damage Functions

Similar to restoration curves, damage functions for ferry system components can be found in Sections 7.2.6 and 7.5.6.

7.7 Airport Transportation System

This section presents an earthquake loss estimation methodology for an airport transportation system. Airport transportation systems consists of runways, control towers, fuel facilities, terminal buildings, maintenance facilities, hangar facilities, and parking structures. For airports, control towers are often constructed of reinforced concrete, while terminal buildings and maintenance facilities are often constructed of structural steel or reinforced concrete. Fuel facilities are similar to those for railway transportation systems.

The scope of this section includes development of methods for estimation of earthquake damage to an airport transportation system given knowledge of components (i.e., runways, control towers, fuel and maintenance facilities, terminal buildings, and parking structures), classification, and hazards (i.e., peak ground acceleration and/or permanent ground deformation).

Damage states describing the level of damage to each of the airport system components are defined (i.e., None, Slight, Moderate, Extensive, or Complete). Damage states are related to damage ratio (defined as ratio of repair to replacement cost) for evaluation of direct economic loss. Fragility curves are developed for each component class of the airport system. These curves describe the probability of reaching or exceeding each damage state given the level of ground motion or ground failure.

Evaluation of component functionality is done in a manner similar to that used for highway and railway components. Component restoration curves are provided for each damage state to evaluate loss of function. Restoration curves describe the fraction or percentage of the component that is expected to be open or operational as a function of time following the earthquake. For airports, the restoration is dependent upon the extent of damage to the airport terminals, buildings, storage tanks (for fuel facilities), control tower, and runways.

7.7.1 Input Requirements and Output Information

Required input to estimate damage to airport systems includes the following items:

- Runways
    - Geographic location of airport (longitude and latitude)
    - PGD
- Control Tower
    - Classification (i.e., building type)
    - Geographic location of structure (longitude and latitude)
    - Spectral acceleration (SA) and PGD
- Fuel Facilities
    - Classification (i.e., with or without anchored equipment and backup power)
    - Geographical location of facility (longitude and latitude)
    - PGA and PGD
- Terminal Buildings
    - Classification (i.e., building type)
    - Geographical location of structure (longitude and latitude)
    - SA and PGD
- Maintenance and Hangar Facilities
    - Classification (i.e., building type)
    - Geographical location of facility (longitude and latitude)
    - SA and PGD
- Parking Structures
    - Classification (i.e., building type)
    - Geographical location of structure (longitude and latitude)
    - SA and PGD

Direct damage output for airport systems includes probability estimates of (1) component functionality and (2) physical damage, expressed in terms of the component’s damage ratio. Damage ratios are used as inputs to direct economic loss methods, as described in Section 11.

7.7.2 Form of Damage Functions

Damage functions or fragility curves for all six airport system components mentioned above are lognormal functions that give the probability of reaching or exceeding different levels of damage for a given level of ground motion or ground failure. Each fragility curve is characterized by a median value of ground motion (or failure) and an associated dispersion factor (lognormal standard deviation). Ground motion is quantified in terms of PGA or SA and ground failure is quantified in terms of PGD.

- For runways, the fragility curves are defined in terms of PGD.
- For fuel facilities, the fragility curves are defined in terms of PGA and PGD.
- For control towers and all other facility types, the fragility curves are defined in terms of SA and PGD.

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

7.7.3 Description of Airport Components

An airport system consists of the six components mentioned above: runways, control towers, fuel facilities, maintenance and hangar facilities, and parking structures. This section provides a brief description of each.

Runways: This component consists of well-paved “flat and wide surfaces”.

Control Towers: Control towers consist of a building and the necessary equipment of air control and monitoring.

Fuel Facilities: These have been previously defined in Section 7.2.3 of railway systems.

Terminal Buildings: These are similar to urban stations of railway systems, as described in Section 7.2.3.

Maintenance and Hangar Facilities and Parking Structures: Maintenance and hangar facilities and parking structures are mainly composed of buildings.

7.7.4 Definitions of Damage States

A total of five damage states are defined for airport system components. These are None, Slight, Moderate, Extensive, and Complete.

Slight Damage

- For runways, Slight damage is defined as minor ground settlement or heaving of the runway surface.
- For fuel facilities, Slight damage is the same as that for fuel facilities in the railway module (see Section 7.2.4).
- For control towers, terminal buildings, maintenance and hangar facilities, and parking structures, whose performance is governed by the performance of the buildings themselves, the Slight damage state is defined as Slight damage to the building.

Moderate Damage

- For runways, Moderate damage is defined the same as Slight damage.
- For fuel facilities, Moderate damage is the same as that for fuel facilities in the railway module.
- For control towers, terminal buildings, maintenance and hangar facilities, and parking structures, the Moderate damage state is defined as Moderate damage to the building.

Extensive Damage

- For runways, Extensive damage is defined as considerable ground settlement or considerable heaving of the runway surface.
- For fuel facilities, Extensive damage is the same as that for fuel facilities in the railway module.
- For control towers, terminal buildings, maintenance and hangar facilities, and parking structures, the Extensive damage state is defined as Extensive damage to the building.

Complete Damage

- For runways, Complete damage is defined as extensive ground settlement or excessive heaving of the runway surface.
- For fuel facilities, Complete damage is the same as that for fuel facilities in the railway module.
- For control towers, terminal buildings, maintenance and hangar facilities, and parking structures, the Complete damage state is defined as Complete damage to the building.

7.7.5 Component Restoration Curves

Restoration Curves are developed based on a best fit to ATC-13 (ATC, 1985) data for social functions SF 27.a and SF 27.b, consistent with damage states defined in the previous section. Normally distributed functions are used to approximate these restoration curves, as was done for highway and railway systems. Means and dispersions of these restoration functions are given in Table 7-21 (except for fuel facilities, which are the same as those for railway fuel facilities, given in Table 7-10) and shown in Figure 7-31 and Figure 7-32. The discretized restoration functions are also presented in Table 7-22, where the percentage restoration is shown at selected time intervals. Although not directly used in Hazus, the discretized restoration functions are presented here as guidance.

Table 7-21 Restoration Functions for Airport Components (All Normal Distributions)

Classification	Damage State	Mean (days)	σ (days)
Control Towers, Parking Structures, Hangar Facilities, Terminal Building	Slight	0	0
	Moderate	1.5	1.5
	Extensive	50	50
	Complete	150	120
Runways	Slight/Moderate	2.5	2.5
	Extensive	35	35
	Complete	85	65

Table 7-22 Discretized Restoration Functions for Airport Sub-Components

Classification	Damage State	Functional Percentage				
		1 day	3 days	7 days	30 days	90 days
Control Towers, Parking Structures, Hangar Facilities, Terminal Building	Slight	100	100	100	100	100
	Moderate	37	84	100	100	100
	Extensive	16	17	20	34	79
	Complete	11	11	12	16	31
Runways	Slight/Moderate	27	57	100	100	100
	Extensive	17	18	21	44	95
	Complete	10	11	12	20	53

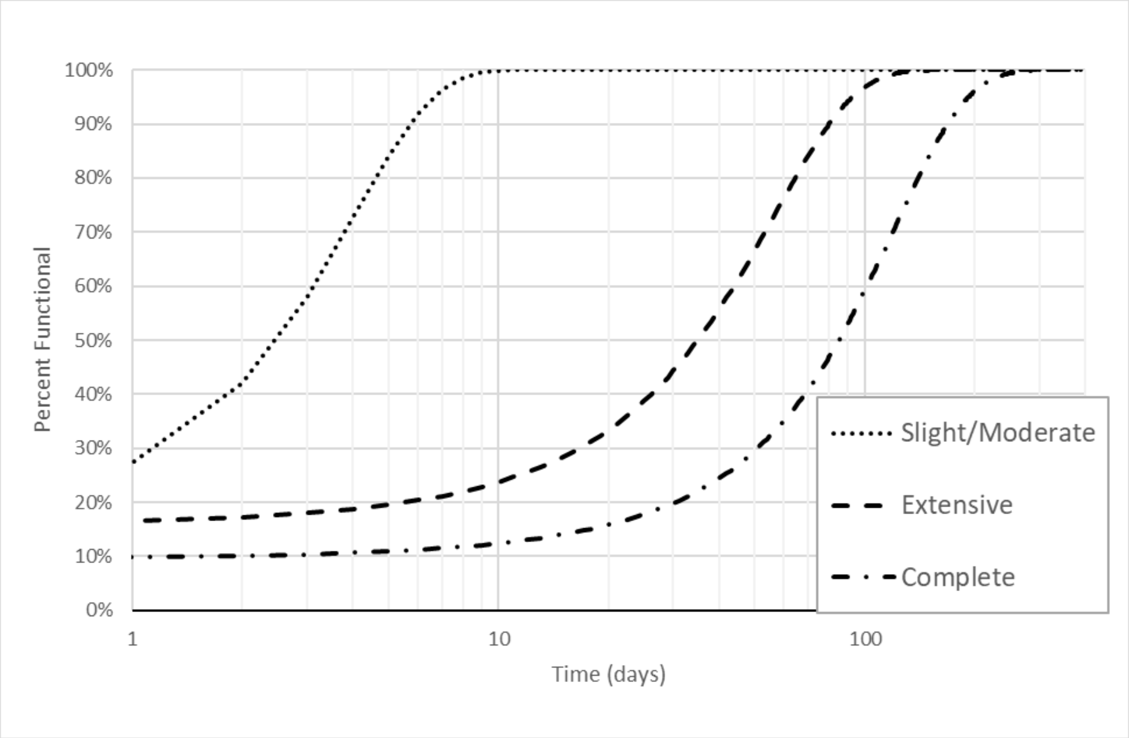


Figure 7-31 Restoration Curve for Airport Runways

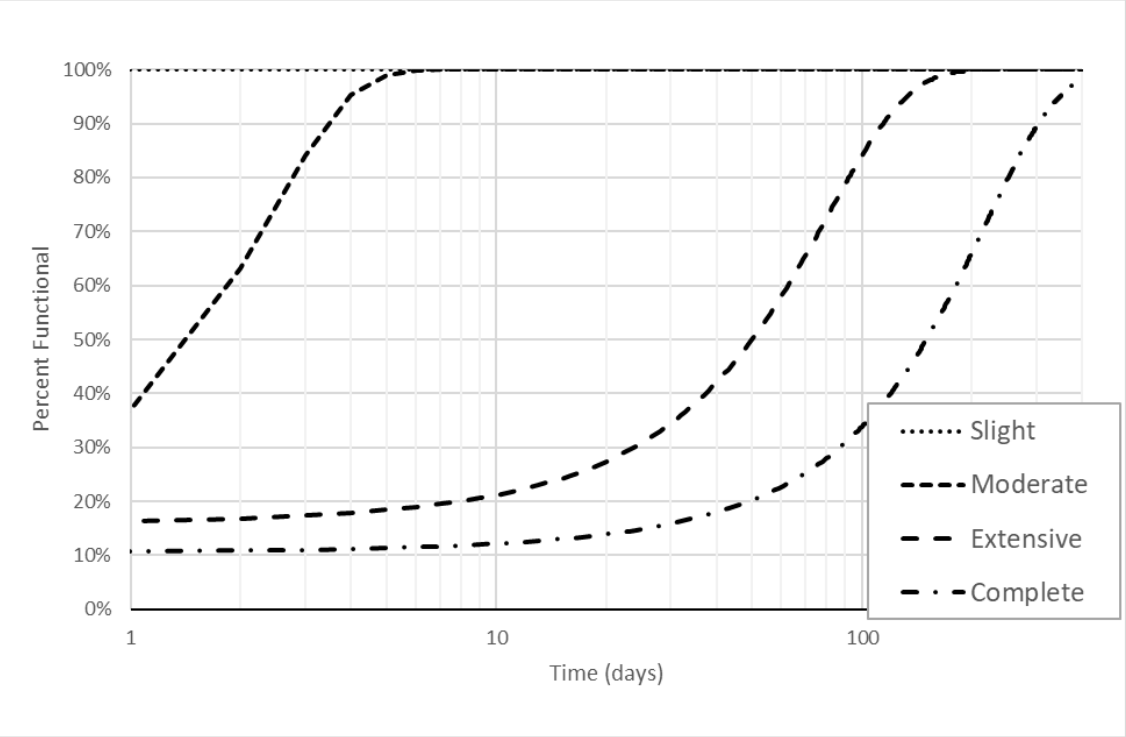


Figure 7-32 Restoration Curves for Airport Buildings, Facilities, and Control Towers

7.7.6 Development of Damage Functions

Damage functions for airport system facilities are defined in terms of PGA or SA and PGD except for runways (PGD only). Note that unless it is specified otherwise, ground failure (PGD) related damage functions for these facilities are assumed to be similar to those described for railroad system facilities in Section 7.2.6. An example of how to combine PGD and PGA damage state probability distributions is presented in Section 7.2.6.2.

7.7.6.1 Damage Functions for Runways

The earthquake hazard for airport runways is ground failure. Little damage is attributed to ground shaking; therefore, the damage function includes only ground failure as the hazard. All runways are assumed to be paved. The median values and dispersion for the fragility curves for the various damage states for runways are given in Table 7-23. These fragility functions are also shown in Figure 7-33.

Table 7-23 Permanent Ground Deformation Fragility Functions for Runways

Classification	Damage State	Median (in)	β
Runways	Slight/Moderate	1	0.6
	Extensive	4	0.6
	Complete	12	0.6

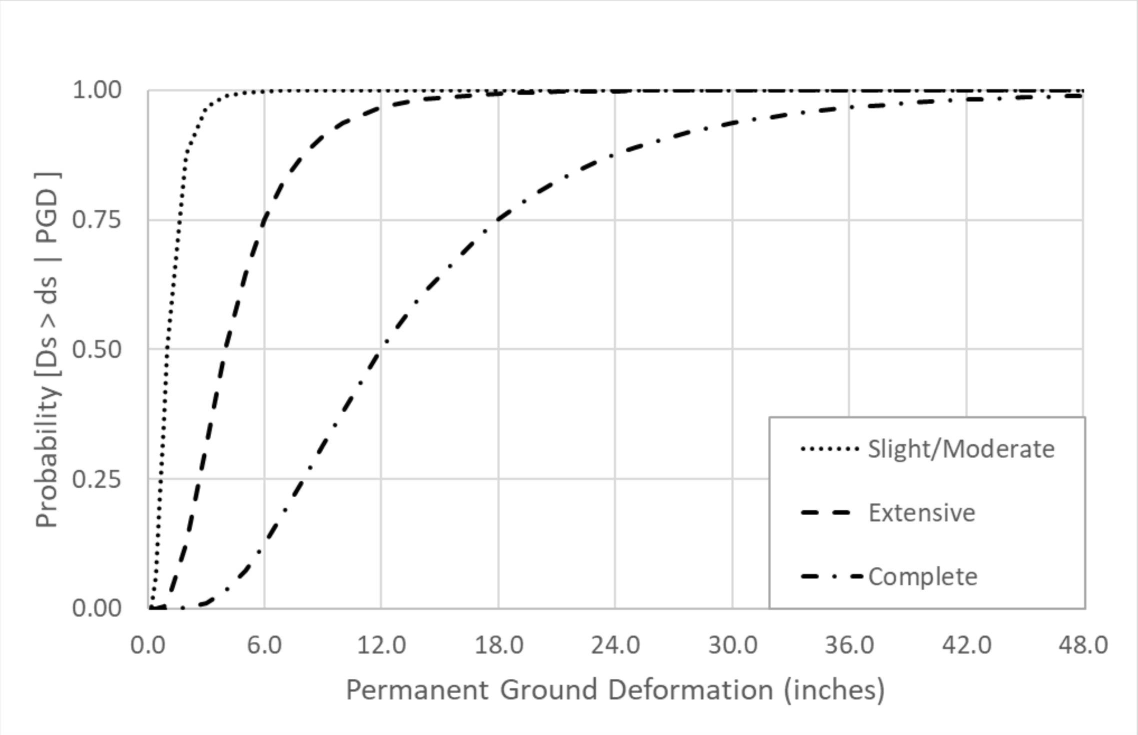


Figure 7-33 Fragility Curves for Runways Subject to Permanent Ground Deformation

7.7.6.2 Damage Functions for Other Airport System Components

Damage functions for airport fuel facilities are similar to those for railway fuel facilities, as described in Section 7.2.6.1.1. Damage functions for airport buildings (control towers, maintenance and hangar facilities, parking structures, and terminal buildings) are similar to standard building fragility curves discussed in Section 5.

Section 8. Direct Physical Damage to Utility Systems

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

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

8.1 Potable Water Systems

This section presents an earthquake loss estimation methodology for water systems. These systems consist of supply, storage, transmission, and distribution components. All of these components are vulnerable to damage during earthquakes, which may result in a significant disruption to the water utility network.

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 primary components (i.e., tanks, aqueducts, water treatment plants, wells, pumping stations, transmission, and distribution pipelines), classification (i.e., for water treatment plants, small, medium, or large), and the hazards (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., None, Slight, Moderate, Extensive, or Complete), while for pipelines the repair rate in terms of number of repairs per kilometer is the key parameter. Fragility curves are developed for each classification of water system components. 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. Hazus functionality estimates are based solely on physical damage to the building/facility, and do not take emergency response or contingency plans into consideration (e.g., hospitals which could operate their emergency room from the parking lot). Functionality estimates also do not consider direct utility outage or potential cascading effects. While no precise definition of functionality has been developed for the Hazus restoration functions, one interpretation of the Hazus functionality results is as follows:

A "functional" building/facility may be used for its intended purpose, while a "non-functional" building/facility can no longer be used for its intended purpose. The Hazus functionality estimates, which range from 0 – 100 percent, may be interpreted as:

- 0-25% functionality – building/facility is likely to be non-functional
- 25-75% functionality – building/facility is likely to allow limited operations (e.g., selected parts of the building/facility may be used)
- 75-100% functionality – building/facility is likely to be functional

8.1.1 Input Requirements and Output Information

The input required to estimate damage to potable water systems includes the following items:

- Distribution Pipelines
  - Classification (ductile pipe or brittle pipe)
  - Geographical location of pipeline links (polyline segments)
  - Peak ground velocity (PGV) and permanent ground deformation (PGD)
- Water Treatment Plants, Wells, Pumping Stations, and Storage Tanks
  - Classification (e.g., capacity and anchorage)
  - Geographical location of facility (longitude and latitude)
  - PGA and PGD

The baseline inventory data in Hazus includes an estimate of potable water distribution pipeline length, aggregated at the Census tract level. 80% of the pipes are assumed to be brittle with the remaining pipes assumed to be ductile (see the *Hazus Inventory Technical Manual* for additional information on the baseline pipeline inventory data). In addition, peak ground velocity and permanent ground deformation (PGV and PGD) for each Census tract is needed for the analysis. The results from the distribution system analysis include the expected number of leaks and breaks per Census tract.

Other direct damage output 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 11. 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 provided in Section 8.1.7.

8.1.2 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 relationships 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 these fragility curves are presented in the next section.

8.1.3 Description of Potable Water System Components

A potable water system typically consists of terminal reservoirs, water treatment plants, wells, pumping plants, storage tanks, and transmission 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 not assessed in the Hazus 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, and/or 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. Some damage to canals has occurred in historic earthquakes, but the modeling of damage to transmission aqueducts is outside the current scope of the methodology.

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 million gallons per day (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 the main components, as well as 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 7.2.3.

Pumping Plants: 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 (less than 10 mgd capacity), medium (10 to 50 mgd) or large (more than 50 mgd capacity). Pumping plants are also classified with respect to whether the subcomponents (equipment and backup power) are anchored or not. As noted in Section 7.2.3, anchored means equipment designed with special seismic tie downs and tiebacks, while unanchored means equipment installed with manufacturers normal requirements.

Wells: 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: 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 at the time of construction, 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 pipeline. 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 provide a large amount of water for firefighting without excessive pressure loss. Small distribution lines represent the mains that supply water to the user and to the fire hydrants.

8.1.4 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. 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.

8.1.4.1 Damage State Definitions for Components Other than Pipelines

A total of five damage states for potable water system components are defined. These are None, Slight, Moderate, Extensive, and Complete.

Slight Damage

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

- For pumping plants, Slight damage is defined by malfunction of the plant for a short time (less than three days) due to loss of electric power and backup power, if any, or Slight damage to building.
- For wells, Slight damage is defined by malfunction of the well pump and motor for a short time (less than three days) due to loss of electric power and backup power if any, or Slight damage to the building.
- For storage tanks, Slight damage is defined by the tank suffering minor damage, such as minor damage to the tank roof due to water sloshing, minor cracks in concrete tanks, or localized wrinkles in steel tanks, without loss of its contents or functionality.

Moderate Damage

- For water treatment plants, Moderate damage is defined by malfunction of plant for about a week due to loss of electric power and backup power, if any, extensive damage to various equipment, considerable damage to sedimentation basins, considerable damage to chlorination tanks with no loss of contents, or considerable damage to chemical tanks. Loss of water quality is imminent.
- For pumping plants, Moderate damage is defined by the loss of electric power for about a week, considerable damage to mechanical and electrical equipment, or Moderate damage to the building.
- For wells, Moderate damage 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 the building.
- For storage tanks, Moderate damage is defined by the tank being considerably damaged, including suffering elephant’s foot buckling for steel tanks without loss of content, or moderate cracking of concrete tanks but with only minor loss of contents.

Extensive Damage

- For water treatment plants, Extensive damage is defined by extensive damage to the pipes connecting the different basins and chemical units. This type of damage will likely result in the shutdown of the plant.
- For pumping plants, Extensive damage is defined by the building being extensively damaged, or the pumps being badly damaged beyond repair.
- For wells, Extensive damage is defined by the building being extensively damaged or the well pump and vertical shaft being badly distorted and nonfunctional.
- For storage tanks, Extensive damage is defined by the tank being severely damaged and going out of service. Typical damage would include elephant’s foot buckling for steel tanks with loss of content, stretching of bars for wood tanks, or shearing of wall for concrete tanks.

Complete Damage

- For water treatment plants, Complete damage is defined by the complete failure of all piping, or extensive damage to the filter gallery.

- For pumping plants, Complete damage is defined by Complete damage to the building; at this level of damage, the performance of the building governs the facility's overall damage state.
- For wells, Complete damage is defined by Complete damage to the building; at this level of damage, the performance of the building governs the facility's overall damage state.
- For storage tanks, Complete damage is defined by the tank collapsing and losing all of its contents.

8.1.4.2 Definition of Damage States for Pipelines

For pipelines, two damage states are considered: 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, which generally cause leaks. In the Hazus 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.

8.1.5 Component Restoration Curves

Restoration functions for potable water system components, namely, water treatment plants, wells, pumping plants, and storage tanks are based on Social Function classifications SF-30a, SF-30b and SF-30d of ATC-13 (ATC, 1985), consistent with damage states defined in the previous section. That is, restoration functions for Slight, Moderate, Extensive, and Complete defined herein are assumed to correspond to Slight, Moderate, Extensive, and Complete of ATC-13. Normally distributed functions are used to approximate these restoration curves, as was done for transportation systems. The parameters of these restoration curves are given in Table 8-1, Table 8-2, and Table 8-3. These restoration functions are also shown in Figure 8-1 through Figure 8-4. Table 8-1 gives means and standard deviations for each restoration curve (i.e., smooth continuous curve) that is used by Hazus, while Table 8-2 gives approximate discrete functions for the restoration curves developed. Although not directly used in Hazus, the discretized restoration functions are presented here as guidance.

Table 8-1 Continuous Restoration Functions for Potable Water Systems (All Normal Distributions

Classification	Damage State	Mean (days)	σ (days)
Water Treatment Plants	Slight	0.9	0.3
	Moderate	1.9	1.2
	Extensive	32	31
	Complete	95	65
Pumping Plants	Slight	0.9	0.3
	Moderate	3.1	2.7
	Extensive	13.5	10
	Complete	35	18
Wells	Slight	0.8	0.2
	Moderate	1.5	1.2
	Extensive	10.5	7.5
	Complete	26	14

Classification	Damage State	Mean (days)	σ (days)
Water Storage Tanks	Slight	1.2	0.4
	Moderate	3.1	2.7
	Extensive	93	85
	Complete	155	120

Table 8-2 Discretized Restoration Functions for Potable Water System Components

Classification	Damage State	Functional Percentage				
		1 day	3 days	7 days	30 days	90 days
Water Treatment Plants	Slight	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	65	100	100	100	100
	Moderate	22	50	93	100	100
	Extensive	10	15	25	95	100
	Complete	3	4	6	40	100
Wells	Slight	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	30	100	100	100	100
	Moderate	20	49	93	100	100
	Extensive	13	15	16	23	40
	Complete	10	11	12	15	30

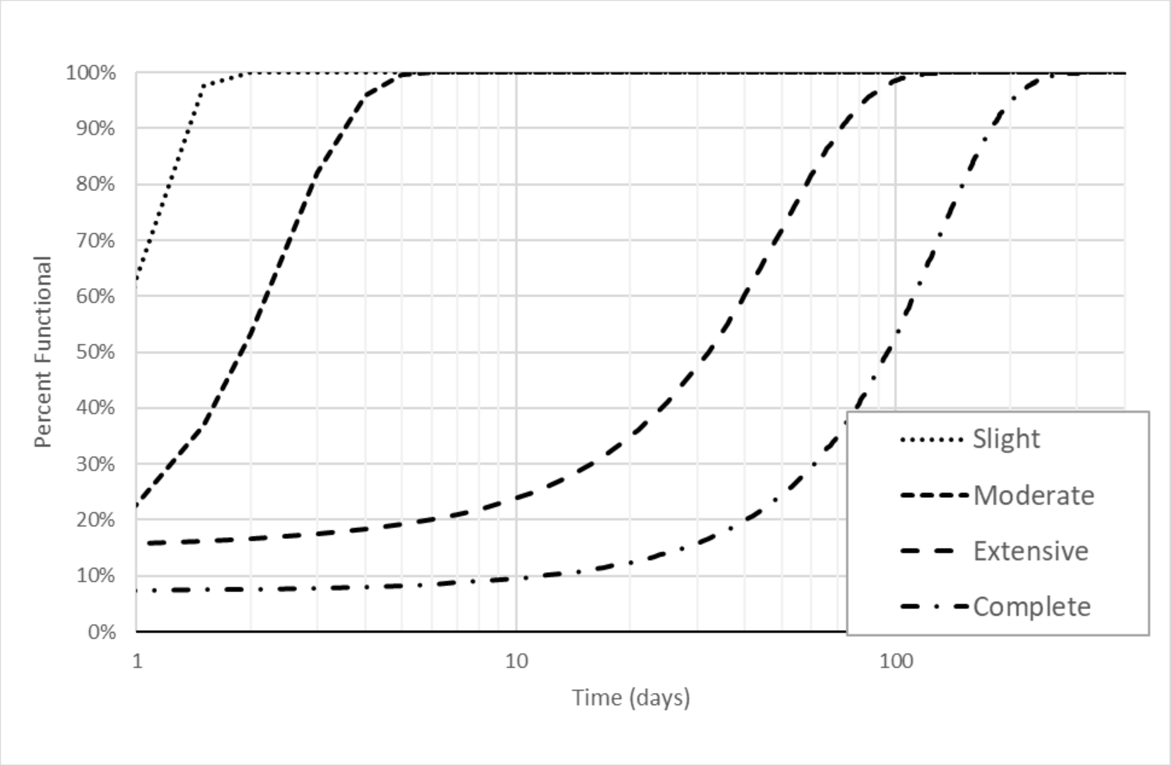


Figure 8-1 Restoration Curves for Water Treatment Plants

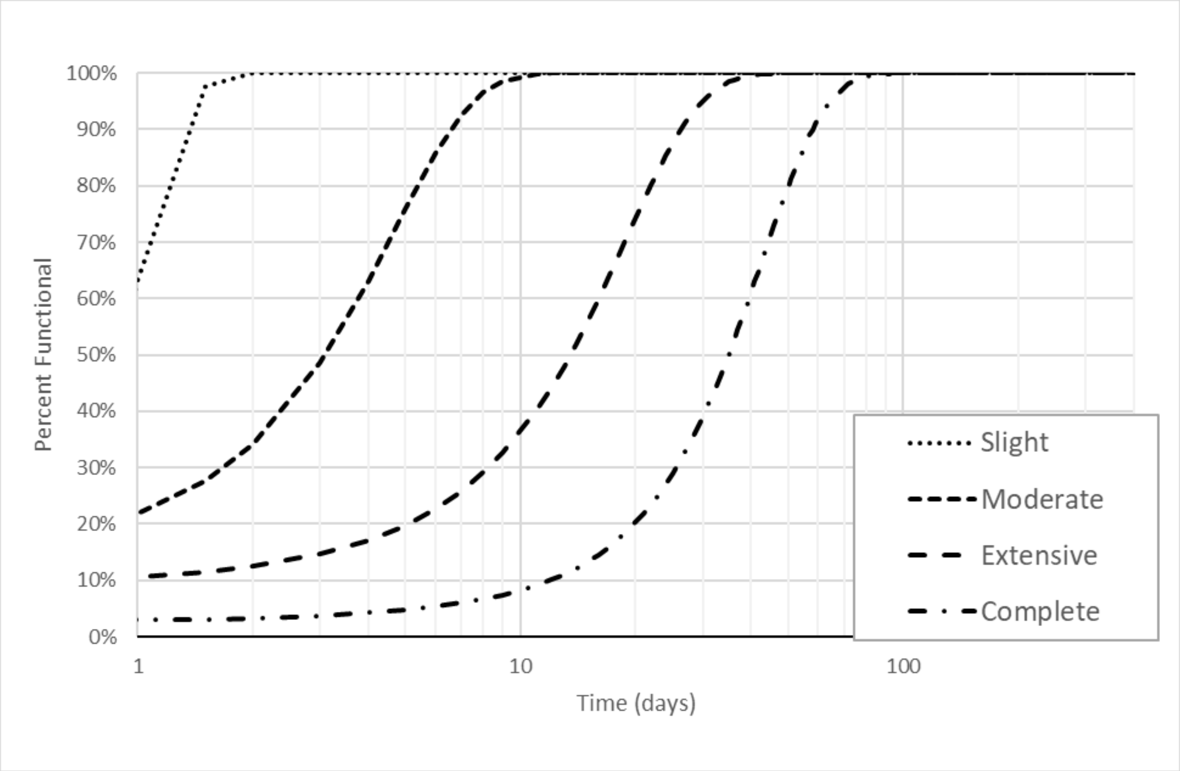


Figure 8-2 Restoration Curves for Pumping Plants

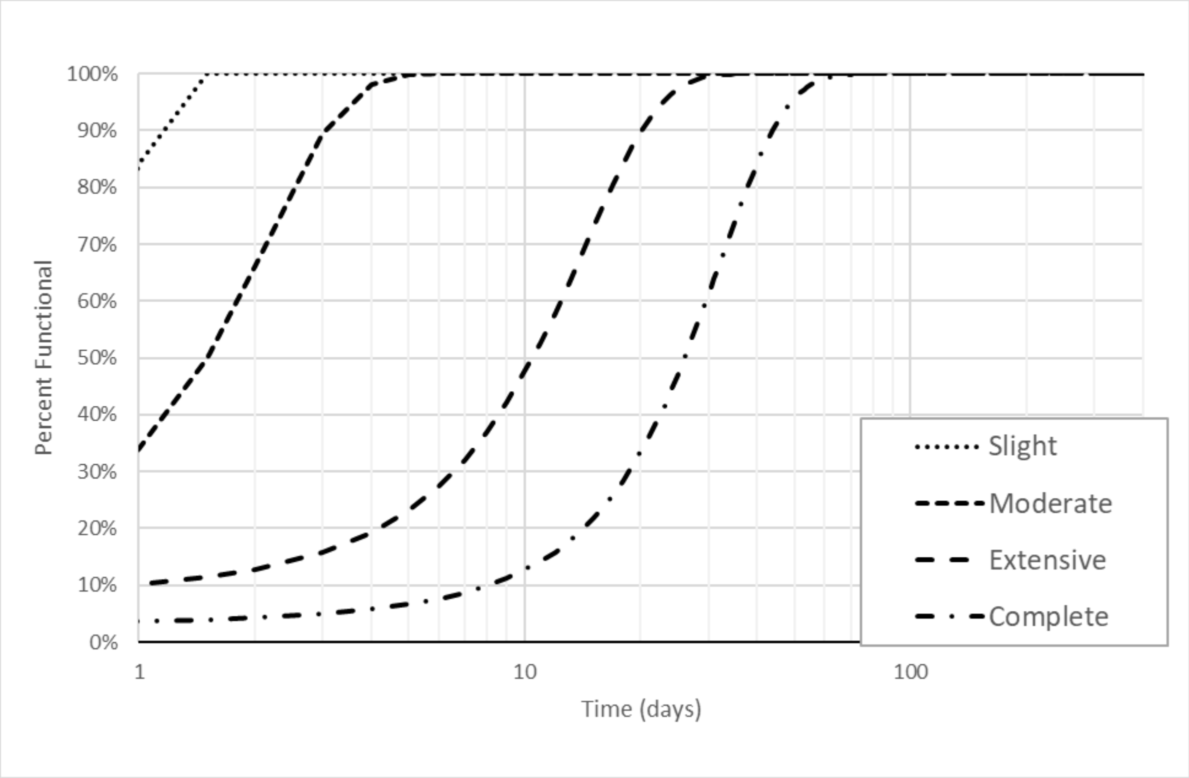


Figure 8-3 Restoration Curves for Wells

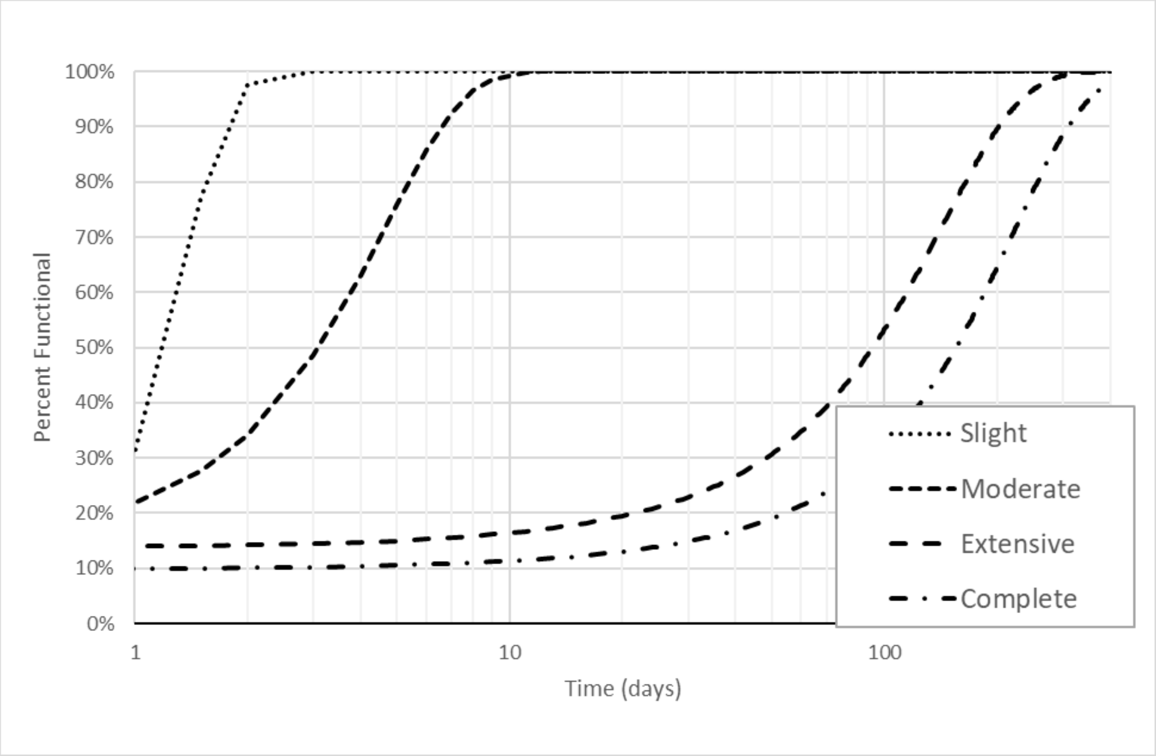


Figure 8-4 Restoration Curves for Water Storage Tanks

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 8-3.

Table 8-3 Restoration Functions for Potable Water Pipelines

Class	Diameter from: [in]	Diameter to: [in]	# Fixed Breaks/Day/ Worker	# Fixed Leaks/Day /Worker	# Available Workers for Leaks & Breaks	Priority
a	60	300	0.2	0.4	100	1 (Highest)
b	36	60	0.2	0.4	100	2
c	20	36	0.2	0.4	100	3
d	12	20	0.5	1	100	4
e	8	12	0.5	1	100	5
u	< 8, or Unknown Diameter		0.5	1	100	6 (Lowest)

It should be noted that the values in Table 8-3 are based on the following four assumptions:

- Pipes that are less than or equal to 20” in diameter are defined as small, while pipes with diameter greater than 20” are defined as large.
- For both small and large pipes, a 16-hour day shift is assumed.
- 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).
- For large pipes, a 4-person crew needs 10 hours to fix a leak, while the same 4-person crew needs 20 hours to fix a break. (Mathematically, this is equivalent to say it takes 40 people to fix a leak in one hour and 80 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 workers) * [(# small pipe leaks/1.0) + (# small pipe breaks/0.5) + (# large pipe leaks/0.4) + (# large pipe breaks/0.2)]

The percentage of repairs finished at Day 1, Day 3, Day 7, Day 30, and Day 90 are then computed using linear interpolation.

8.1.6 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 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 damage for a water treatment plant is 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 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. Further information on the potable water system facility subcomponent fragilities can be found in Appendix B.

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 fragility curve 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 60 inches due to lateral spreading, there is a 50% probability of "at least Extensive" damage.
- For vertical settlement, a lognormal fragility 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 inches 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 the “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 PGD and PGA damage state probability distributions for utility system components was presented in Section 7.2.6.2.

8.1.6.1 Damage Functions for Water Treatment Plants

PGA related damage functions for water treatment plants are developed with respect to their classification. Half of the fragility functions correspond to water treatment plants with anchored subcomponents, while the other half correspond to water treatment plants with unanchored subcomponents. Medians and dispersions of these damage functions are given in Table 8-4, Table 8-5, and Table 8-6. Graphical representations of water treatment plant damage functions are also provided. Figure 8-5 through Figure 8-10 are fragility curves for the different classes of water treatment plants. Damage functions available within Hazus are the functions for facilities with unanchored components. User's wishing to analyze facilities with anchored components can revise the existing damage functions through the Hazus menus.

Table 8-4 Peak Ground Acceleration Fragility Functions for Small Water Treatment Plants

Classification	Damage State	Median (g)	β
Small Water Treatment Plants (PWTS) with anchored subcomponents	Slight	0.25	0.50
	Moderate	0.38	0.50
	Extensive	0.53	0.60
	Complete	0.83	0.60
Small Water Treatment Plants (PWTS) with unanchored subcomponents	Slight	0.16	0.40
	Moderate	0.27	0.40
	Extensive	0.53	0.60
	Complete	0.83	0.60

Table 8-5 Peak Ground Acceleration Fragility Functions for Medium Water Treatment Plants

Classification	Damage State	Median (g)	β
Medium Water Treatment Plants (PWTM) with anchored subcomponents	Slight	0.37	0.40
	Moderate	0.52	0.40
	Extensive	0.73	0.50
	Complete	1.28	0.50
Medium Water Treatment Plants (PWTM) with unanchored subcomponents	Slight	0.20	0.40
	Moderate	0.35	0.40
	Extensive	0.75	0.50
	Complete	1.28	0.50

Table 8-6 Peak Ground Acceleration Fragility Functions for Large Water Treatment Plants

Classification	Damage State	Median (g)	β
Large Water Treatment Plants (PWTL) with anchored subcomponents	Slight	0.44	0.40
	Moderate	0.58	0.40
	Extensive	0.87	0.45
	Complete	1.57	0.45
Large Water Treatment Plants (PWTL) with unanchored subcomponents	Slight	0.22	0.40
	Moderate	0.35	0.40
	Extensive	0.87	0.45
	Complete	1.57	0.45

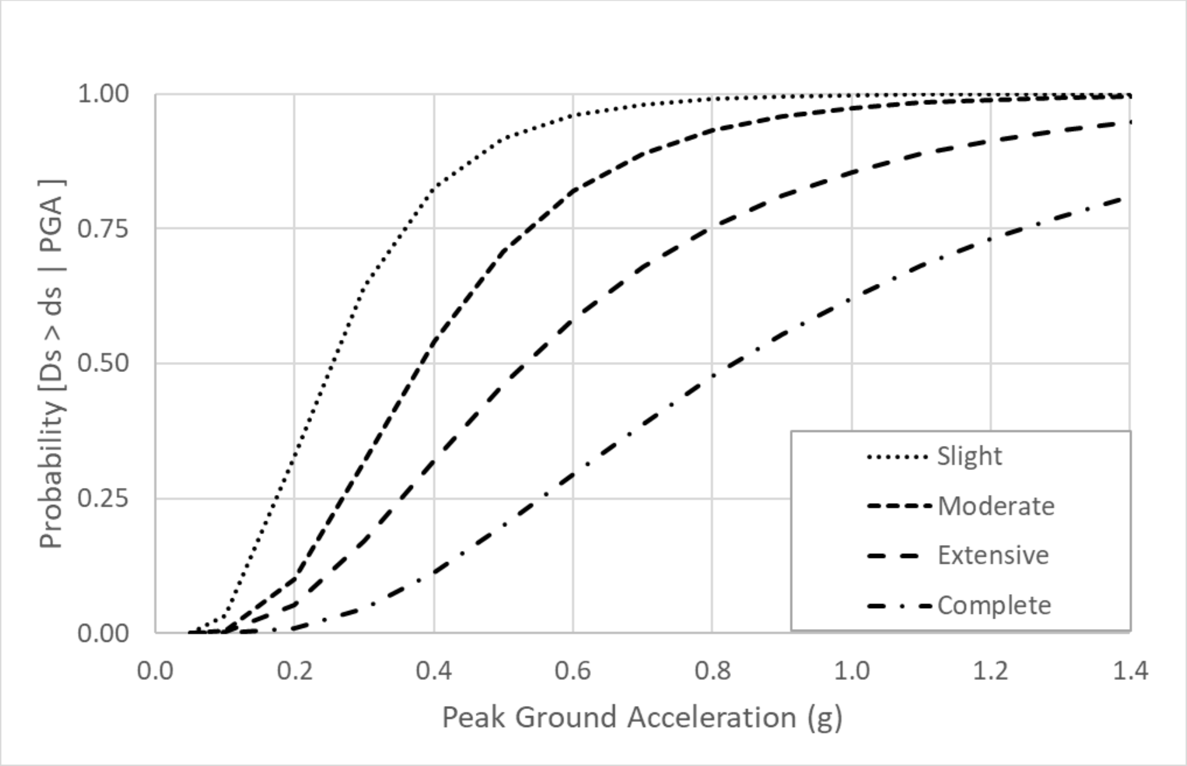


Figure 8-5 Fragility Curves for Small Water Treatment Plants with Anchored Components

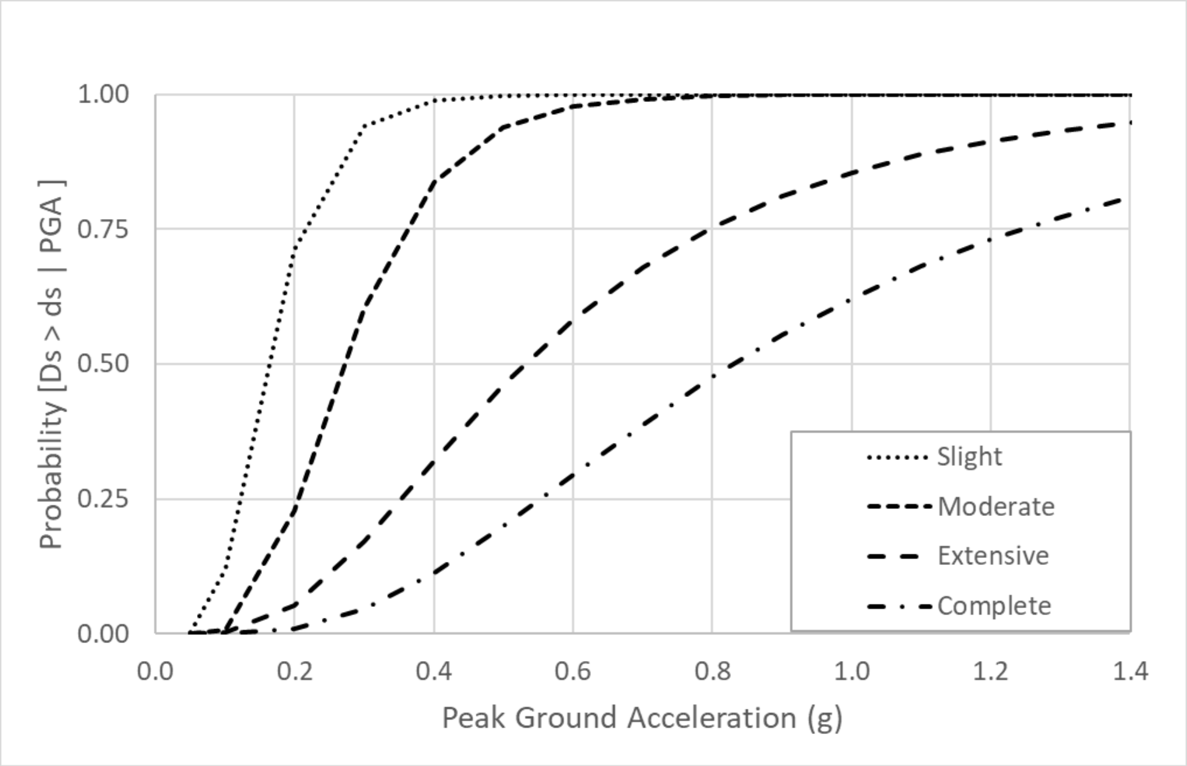


Figure 8-6 Fragility Curves for Small Water Treatment Plants with Unanchored Components

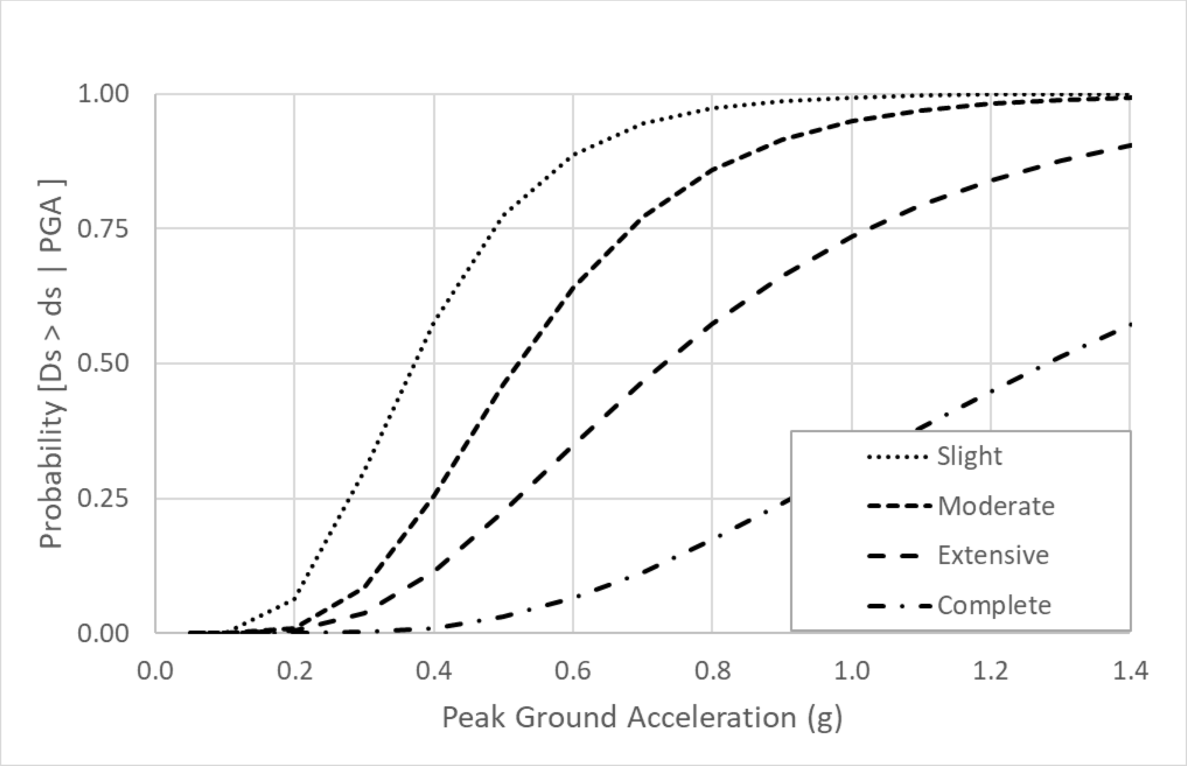


Figure 8-7 Fragility Curves for Medium Water Treatment Plants with Anchored Components

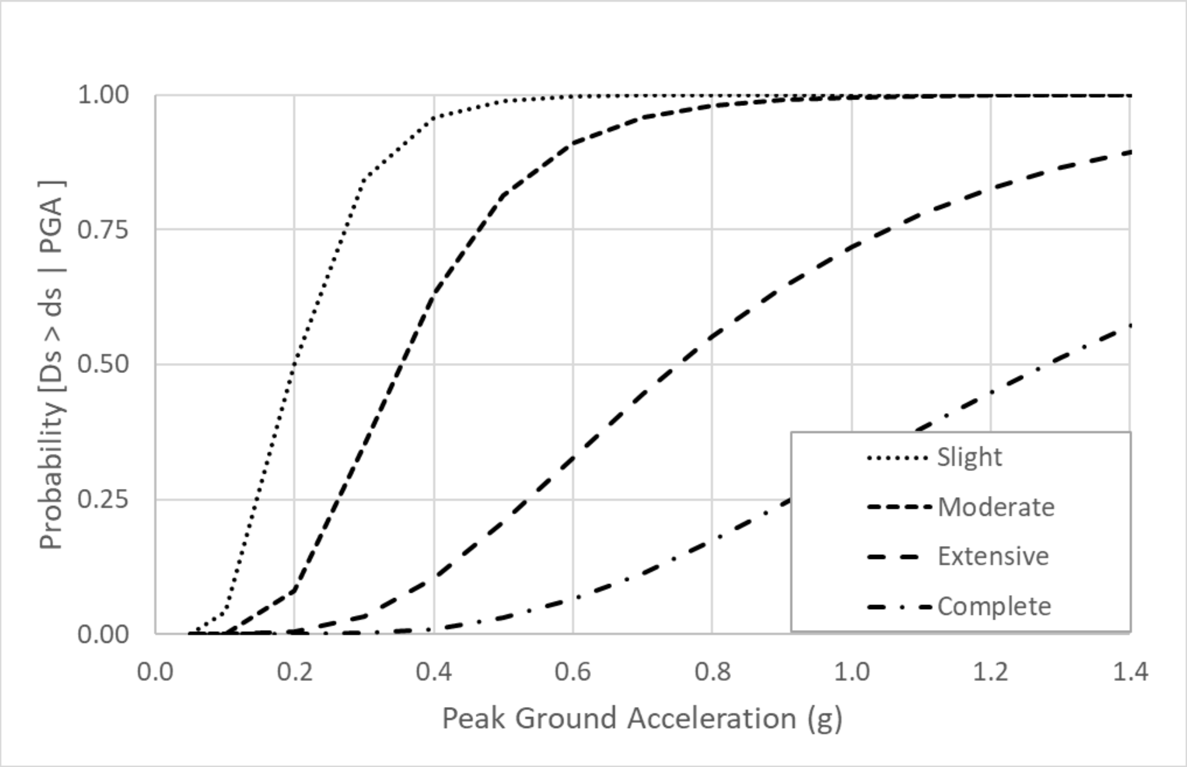


Figure 8-8 Fragility Curves for Medium Water Treatment Plants with Unanchored Components

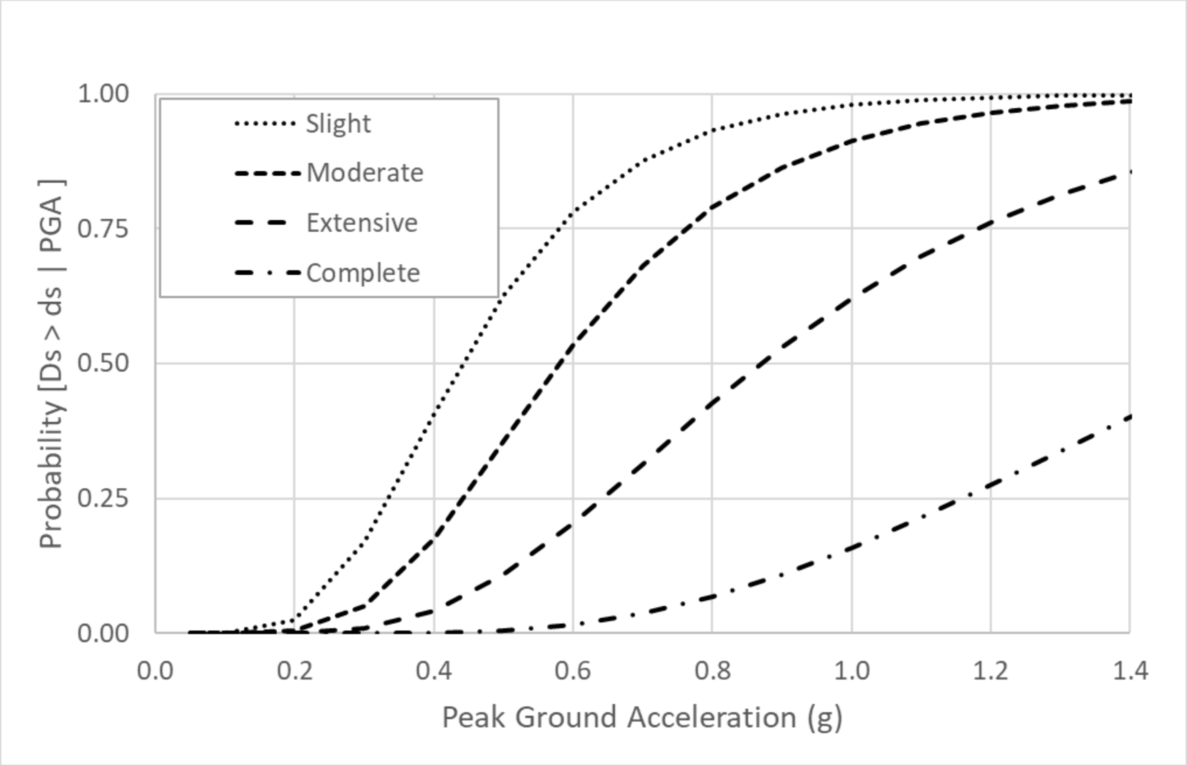


Figure 8-9 Fragility Curves for Large Water Treatment Plants with Anchored Components

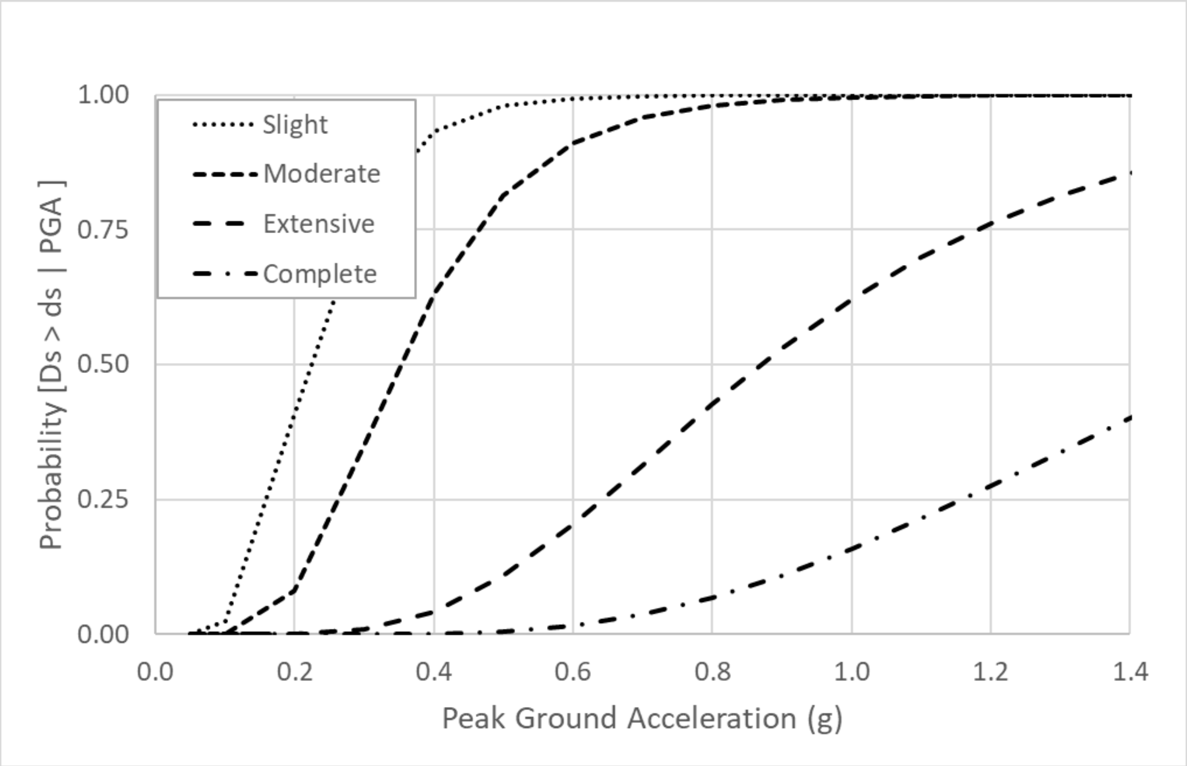


Figure 8-10 Fragility Curves for Large Water Treatment Plants with Unanchored Components

8.1.6.2 Damage Functions for Pumping Plants

PGA related damage functions for pumping plants are developed with respect to their classification. Half of the 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 Table 8-7 and Table 8-8. Graphical representations of fragility functions for the different classes of pumping plants are presented in Figure 8-11 through Figure 8-14. Damage functions available within Hazus are the functions for facilities with unanchored components. User's wishing to analyze facilities with anchored components can revise the existing damage functions through the Hazus menus.

Table 8-7 Peak Ground Acceleration Fragility Functions for Small Pumping Plants

Classification	Damage State	Median (g)	β
Small Pumping Plants (PPPS) with anchored subcomponents	Slight	0.15	0.70
	Moderate	0.36	0.65
	Extensive	0.66	0.65
	Complete	1.50	0.80
Small Pumping Plants (PPPS) with unanchored subcomponents	Slight	0.13	0.60
	Moderate	0.28	0.50
	Extensive	0.66	0.65
	Complete	1.50	0.80

Table 8-8 Peak Ground Acceleration Fragility Functions for Medium/Large Pumping Plants

Classification	Damage State	Median (g)	β
Medium (PPPM) and Large (PPPL) Pumping Plants with anchored subcomponents	Slight	0.15	0.75
	Moderate	0.36	0.65
	Extensive	0.77	0.65
	Complete	1.50	0.80
Medium (PPPM) and Large (PPPL) Pumping Plants with unanchored subcomponents	Slight	0.13	0.60
	Moderate	0.28	0.50
	Extensive	0.77	0.65
	Complete	1.50	0.80

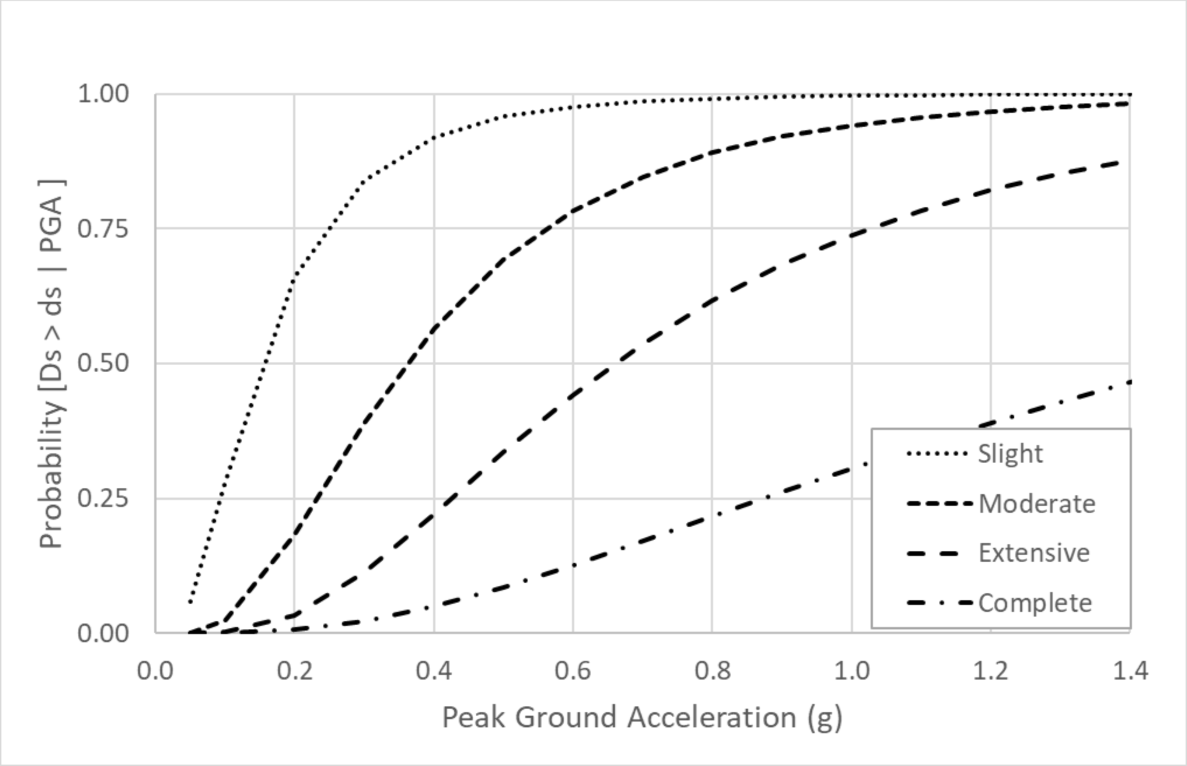


Figure 8-11 Fragility Curves for Small Pumping Plants with Anchored Components

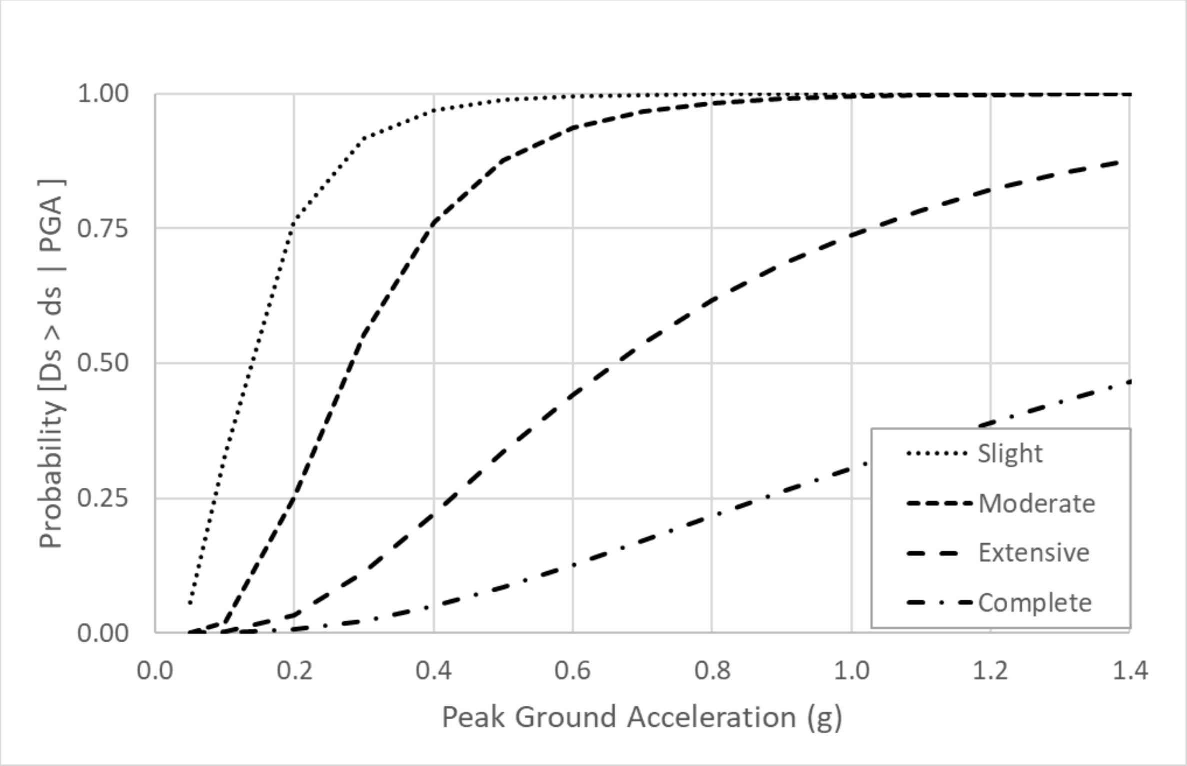


Figure 8-12 Fragility Curves for Small Pumping Plants with Unanchored Components

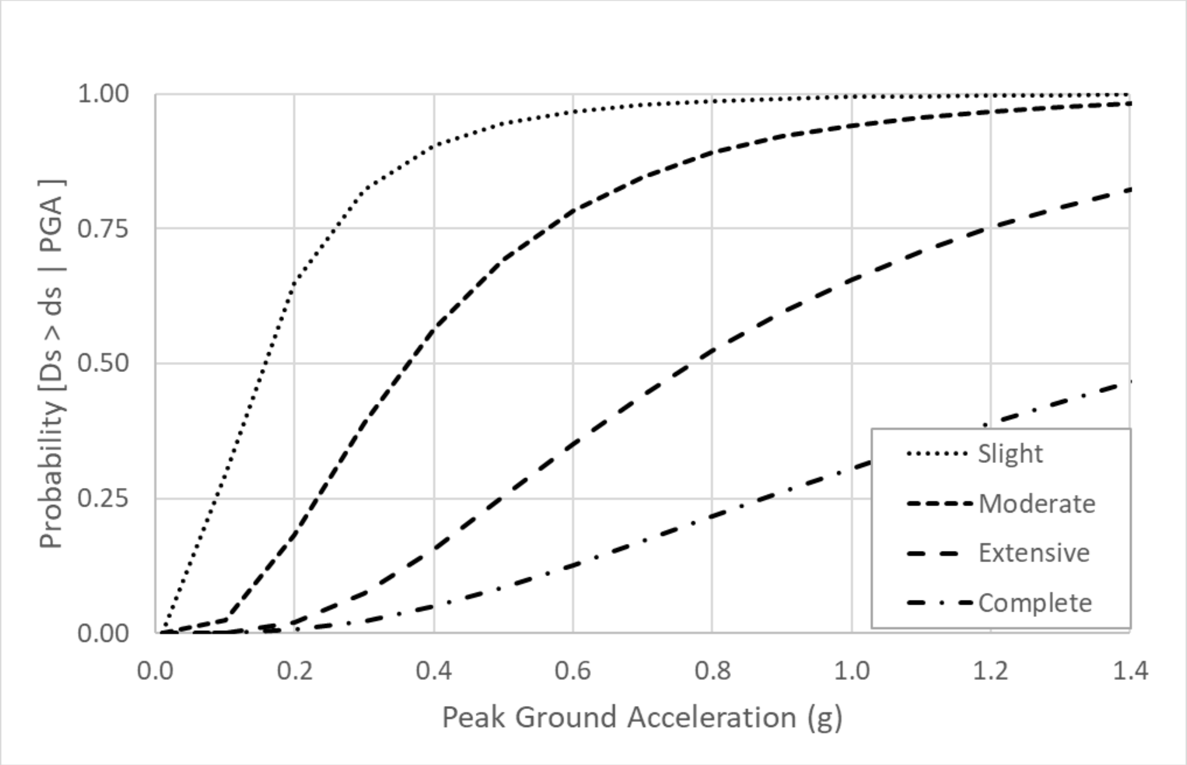


Figure 8-13 Fragility Curves for Medium/Large Pumping Plants with Anchored Components

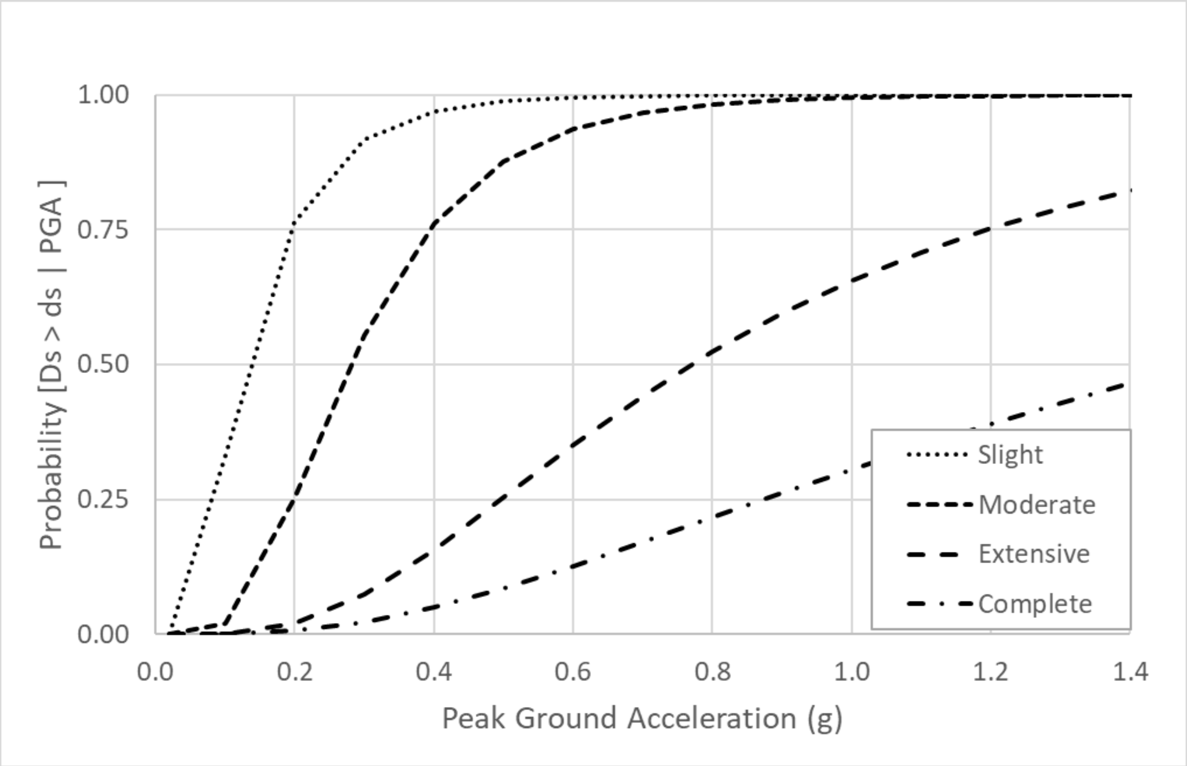


Figure 8-14 Fragility Curves for Medium/Large Pumping Plants with Anchored Components

8.1.6.3 Damage Functions for Wells

Medians and dispersion for the PGA-related damage functions for wells are presented in Table 8-9 Peak Ground Acceleration Fragility Functions for Wells. In developing these damage functions, it is assumed that equipment in wells is anchored. Graphical representations of well damage functions are shown in Figure 8-15.

Table 8-9 Peak Ground Acceleration Fragility Functions for Wells

Classification	Damage State	Median (g)	β
Wells (PWE)	Slight	0.15	0.75
	Moderate	0.36	0.65
	Extensive	0.72	0.65
	Complete	1.50	0.80

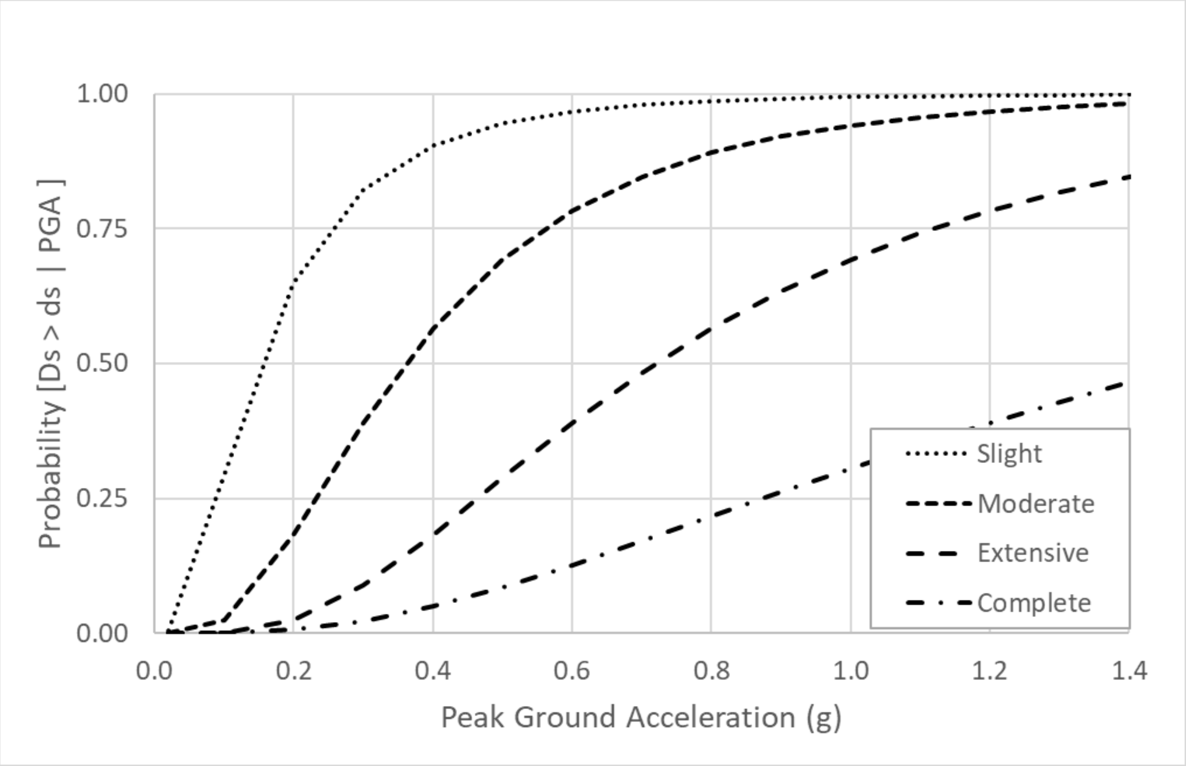


Figure 8-15 Fragility Curves for Wells

8.1.6.4 Damage Functions for Water Storage Tanks

PGA-related damage functions are provided for on-ground concrete tanks (anchored and unanchored), on ground steel tanks (anchored and unanchored), elevated steel tanks, 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 fragility functions associated with these water storage tanks was described at the beginning of Section 8.1.6. For buried storage tanks, a separate PGD fragility function is presented. Medians and dispersions of the PGA related fragility functions are given in Table 8-10 and Table 8-11. Graphical representations of water storage tank damage functions are also provided. Figure 8-16 through Figure 8-22 provide the fragility curves for the different classes of water storage tanks.

Table 8-10 Peak Ground Acceleration Fragility Functions for Water Storage Tanks

Classification	Damage State	Median (g)	β
On-Ground Concrete Tank (PSTGC), Anchored	Slight	0.25	0.55
	Moderate	0.52	0.70
	Extensive	0.95	0.60
	Complete	1.64	0.70
On-Ground Concrete Tank (PSTGC), Unanchored	Slight	0.18	0.60
	Moderate	0.42	0.70
	Extensive	0.70	0.55
	Complete	1.04	0.60
On-Ground Steel Tank (PSTGS), Anchored	Slight	0.30	0.60
	Moderate	0.70	0.60
	Extensive	1.25	0.65
	Complete	1.60	0.60
On-Ground Steel Tank (PSTGS), Unanchored	Slight	0.15	0.70
	Moderate	0.35	0.75
	Extensive	0.68	0.75
	Complete	0.95	0.70
Above-Ground Steel Tank (PSTAS)	Slight	0.18	0.50
	Moderate	0.55	0.50
	Extensive	1.15	0.60
	Complete	1.50	0.60
On-Ground Wood Tank (PSTGW)	Slight	0.15	0.60
	Moderate	0.40	0.60
	Extensive	0.70	0.70
	Complete	0.90	0.70

Table 8-11 Peak Ground Displacement Fragility Functions for Water Storage Tanks

Classification	Damage State	Median (Inches)	β
Buried Concrete Tank (PSTBC)	Slight	2	0.50
	Moderate	4	0.50
	Extensive	8	0.50
	Complete	12	0.50

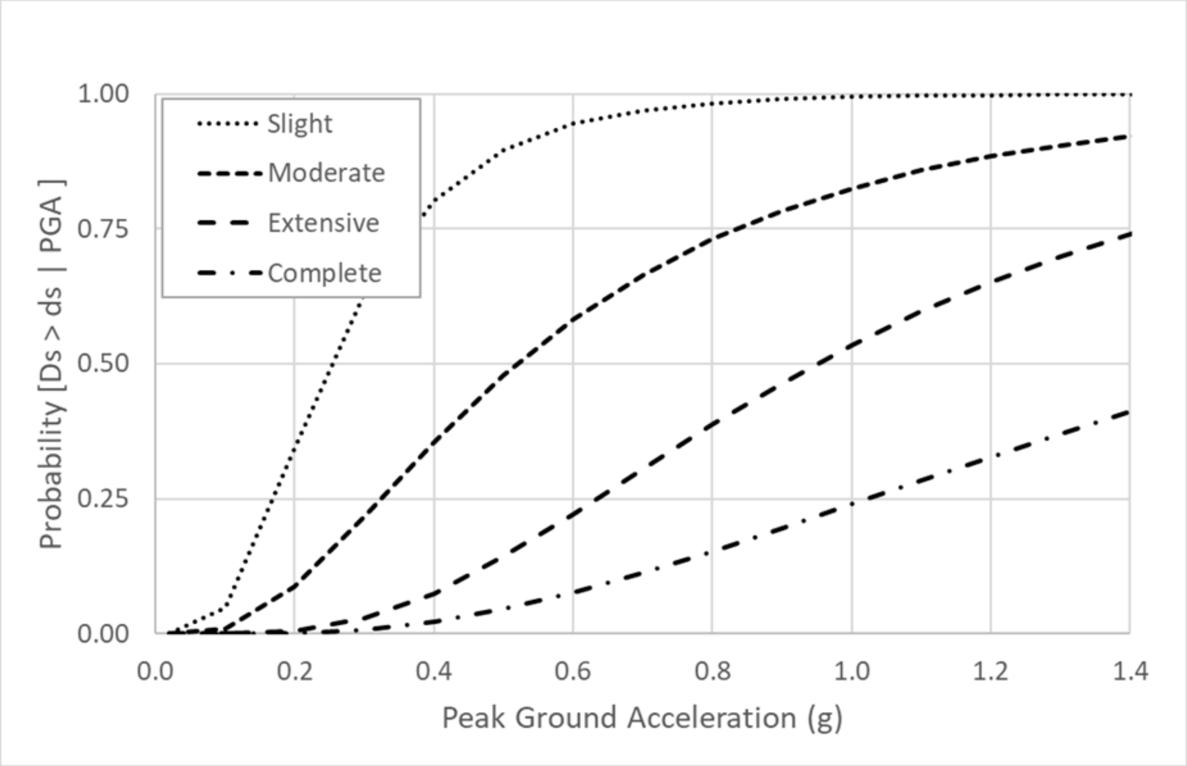


Figure 8-16 Fragility Curves for On-Ground Concrete Tanks, Anchored

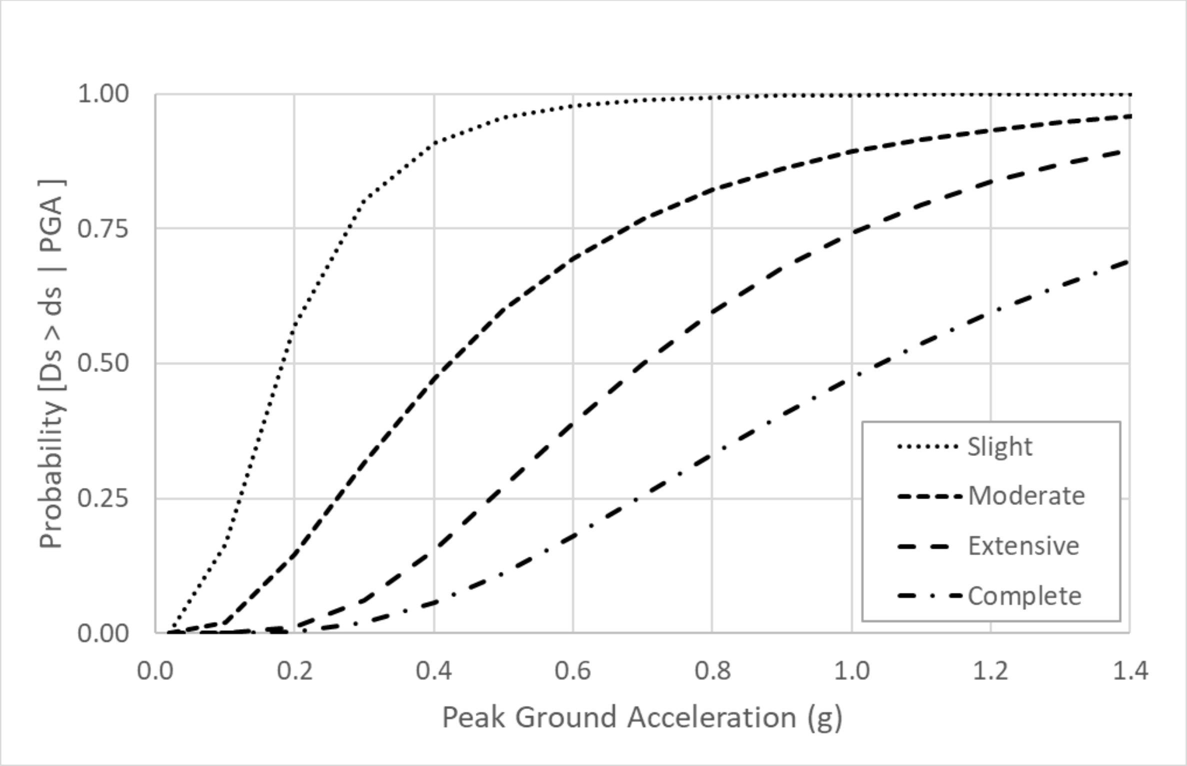


Figure 8-17 Fragility Curves for On-Ground Concrete Tanks, Unanchored

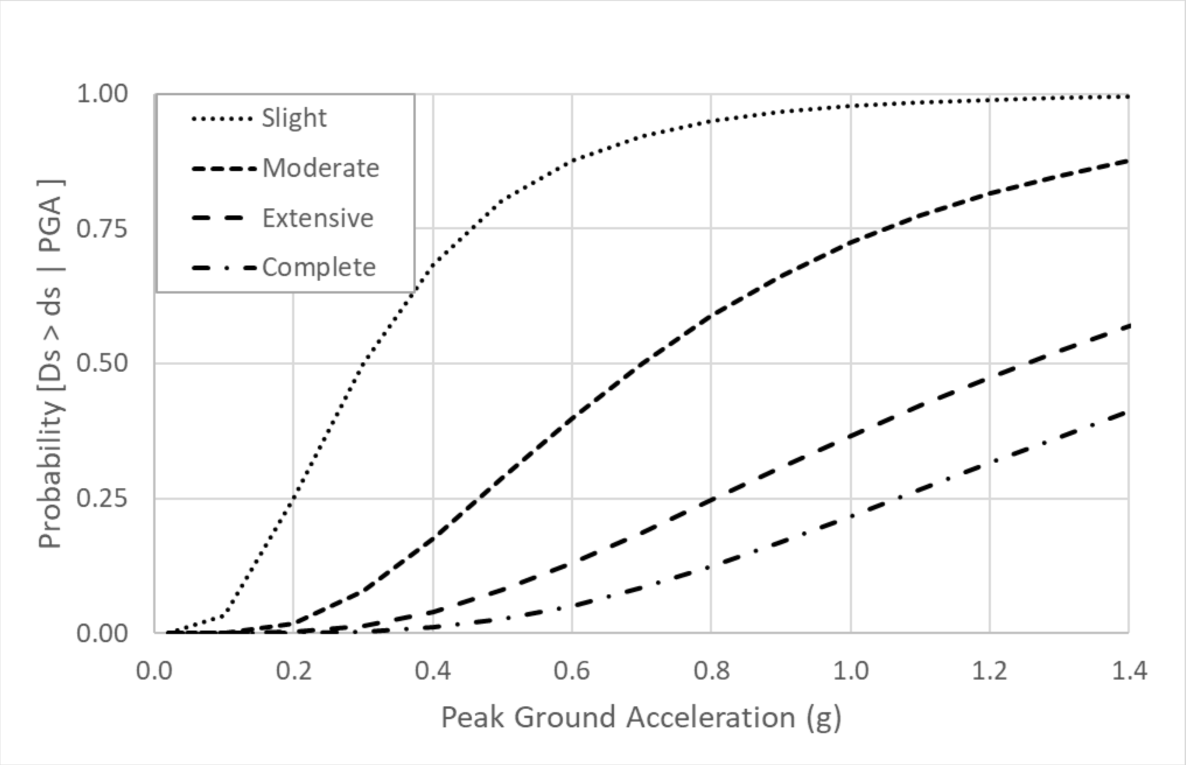


Figure 8-18 Fragility Curves for On-Ground Steel Tanks, Anchored

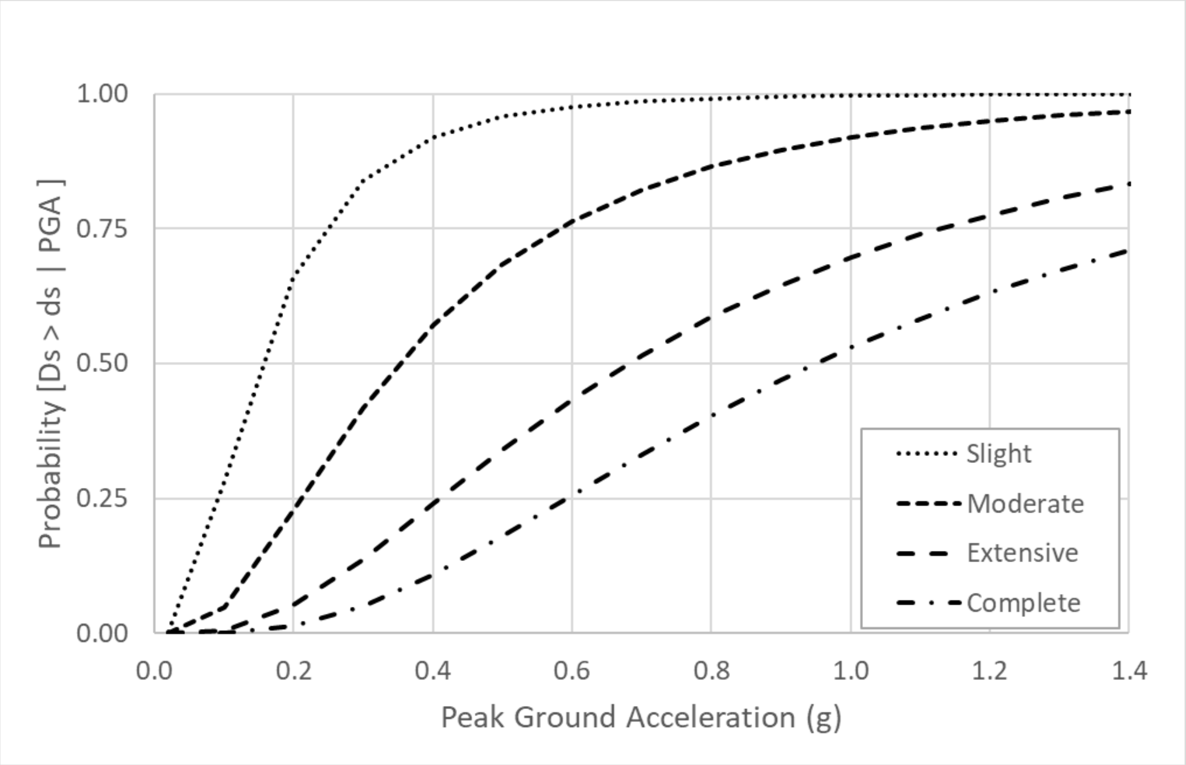


Figure 8-19 Fragility Curves for On-Ground Steel Tanks, Unanchored

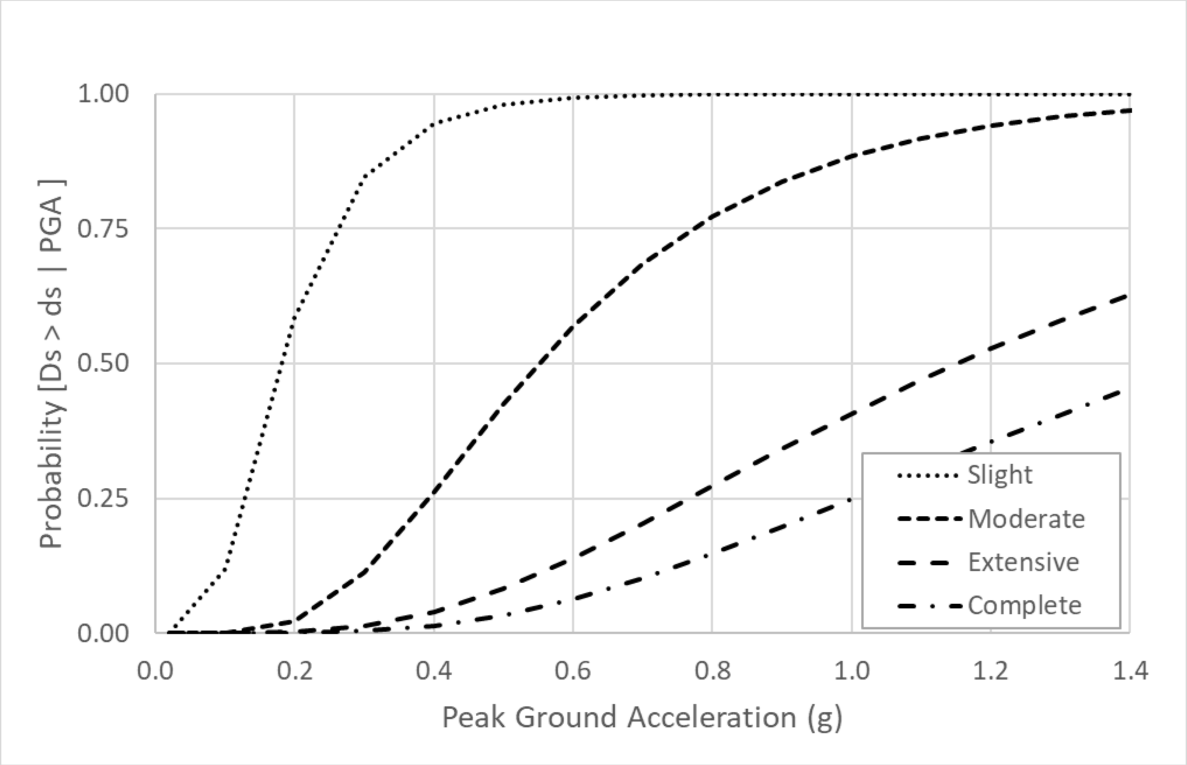


Figure 8-20 Fragility Curves for Above-Ground Steel Tanks

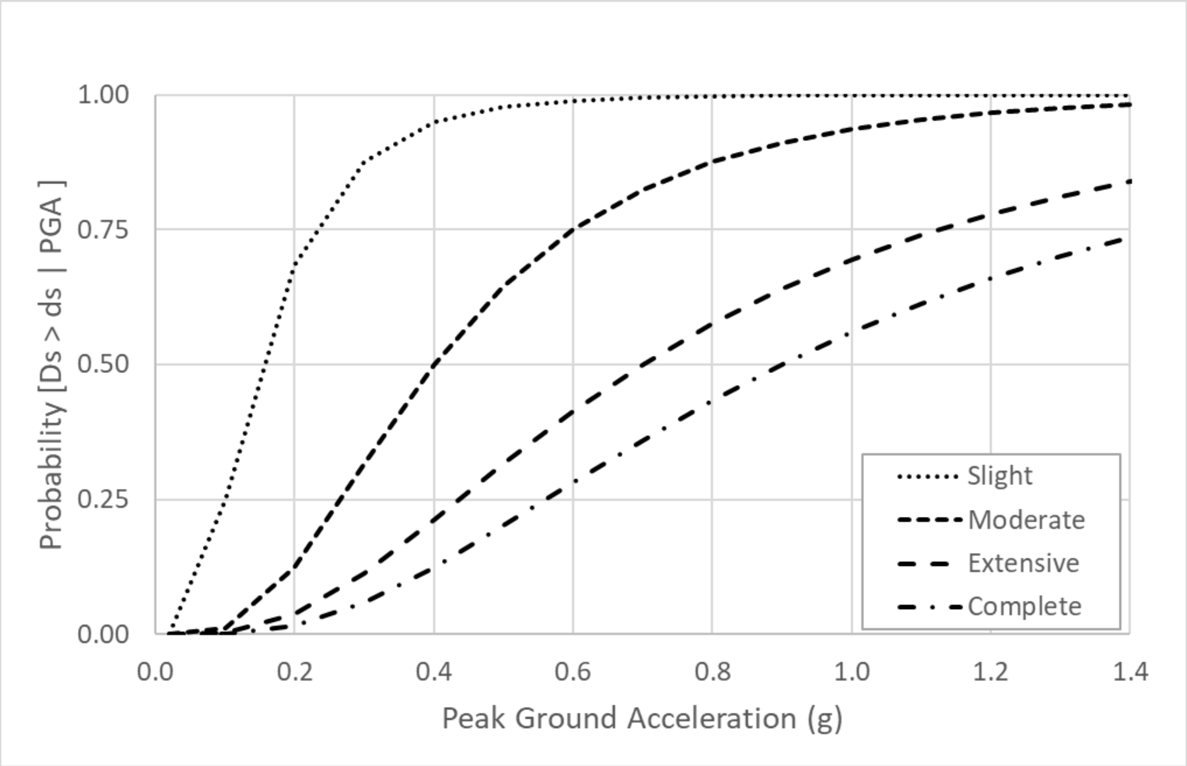


Figure 8-21 Fragility Curves for On-Ground Wood Tanks

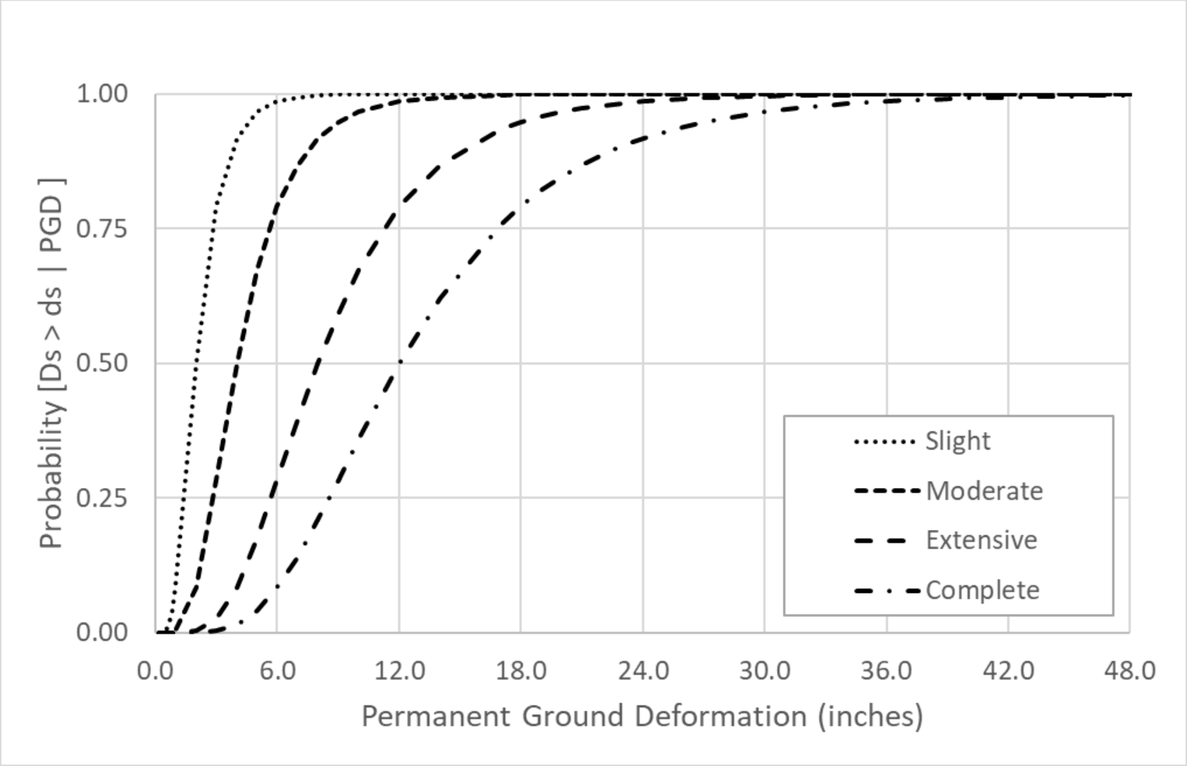


Figure 8-22 Fragility Curves for Buried Concrete Tanks

8.1.6.5 Damage Functions for Buried Pipelines

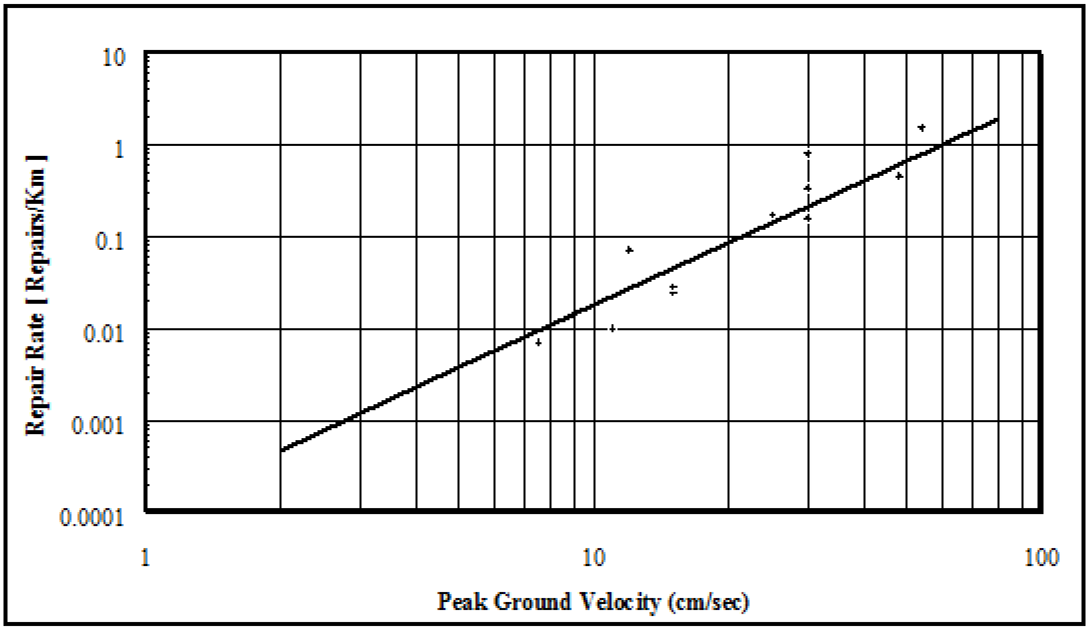
Two damage models are used for buried pipelines. The first model is associated with peak ground velocity (PGV), while the second model is associated with permanent ground deformation (PGD). Note that in both of these models, the diameter of pipe is not considered to be a factor.

The PGV damage model is based on the empirical data presented in work done by O'Rourke and Ayala (1993). The empirical data utilized in that study correspond to actual pipeline damage observed in four U.S. and two Mexican earthquakes. These data are plotted in Figure 8-23. The following relationship provides a good fit for these empirical data, with PGV expressed in cm/sec:

Equation 8-1

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

Note that the data plotted in Figure 8-23 correspond to asbestos cement, concrete, and cast iron pipes; therefore, Equation 8-1 is assumed to apply to brittle pipelines. For ductile pipelines (steel, ductile iron, and PVC), the above relationship 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. If information on steel pipe weld types is unavailable, the user may use year of installation to classify the steel pipelines as ductile or brittle. In this case, the user should classify pre-1935 steel pipes as brittle pipes.



** Based on Four U.S. and Two Mexican Earthquakes*

Figure 8-23 Ground Shaking (Wave Propagation) Damage Model for Brittle Pipes (Specifically CI, AC, RCC, and PCCP)

The damage model 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 8-24 shows the base fragility curve for cast iron pipes. The best-fit function to this curve is given by Equation 8-2, where PGD is expressed in inches.

Equation 8-2

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

This relationship is assumed to apply to brittle pipelines. For ductile pipelines, the same multiplier as the PGV damage model is assumed (i.e., 0.3).

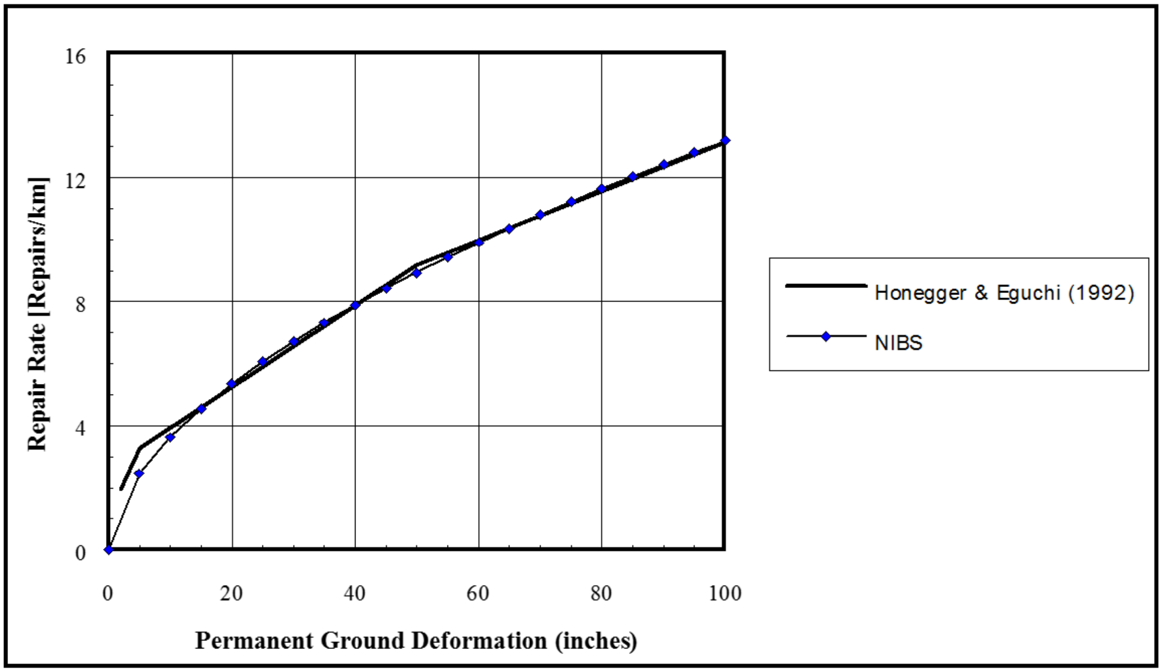


Figure 8-24 Ground Deformation Damage Model for Cast Iron Pipes

To summarize, the pipeline damage models that are used in the current loss estimation methodology are presented in Table 8-12 Damage Models for Water Pipelines.

Table 8-12 Damage Models for Water Pipelines

Pipe Type	PGV Model		PGD Model	
	R. R. ≅ 0.0001 * PGV$^{(2.25)}$		R. R. ≅ Prob[liq] * PGD$^{(0.56)}$	
	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

** CI= Cast Iron, AC = Asbestos Cement, RCC = Reinforced Concrete Cylinder, DI = Ductile Iron, S = Steel, and PVC = Polyvinyl Chloride.*

8.1.7 Water System Performance

In the previous section, fragility curves for the various components of a water system were presented. This section outlines the simplified methodology that is used in the level 1 and level 2 analyses, which allows for a quick evaluation of the water system performance in the aftermath of an earthquake.

This approach is based on system performance studies done for water networks in Oakland, San Francisco, and Tokyo. 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 8-25. The probability of pipeline failure, which was assumed to follow a Poisson process in the original paper, was substituted with the average break rate, which was back calculated 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.

Also shown on Figure 8-25 are the results of several other researchers, including researchers at Cornell University (Markov, Grigoriu, and O'Rourke, 1994) who evaluated the San Francisco auxiliary (fire fighting) water supply system (AWSS), and a study for the EBMUD (East Bay Municipal Utilities District) water supply system (G&E, 1994c).

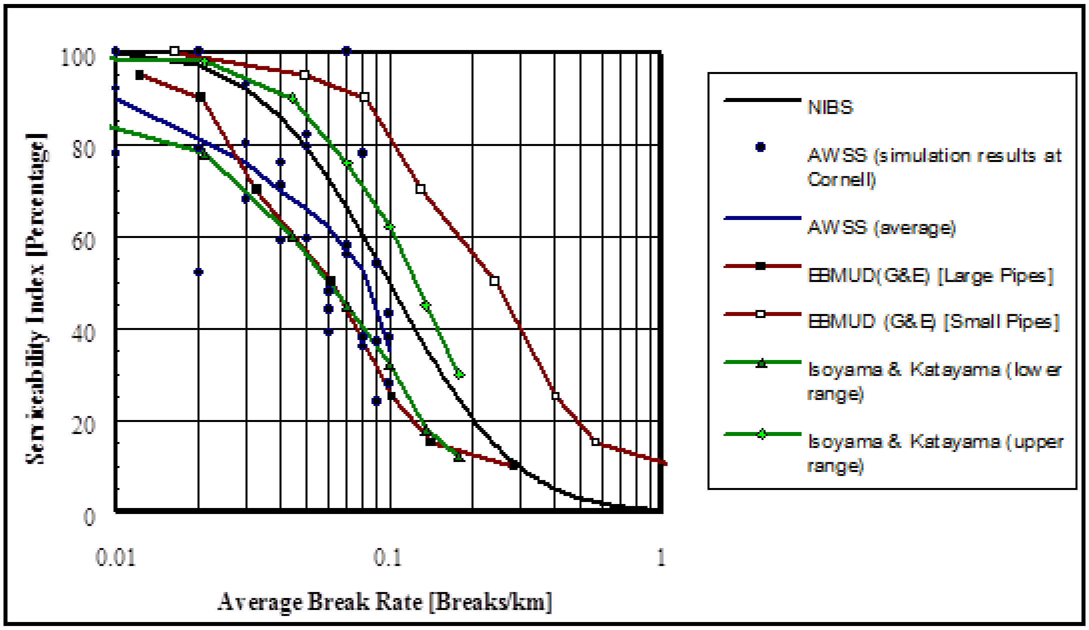


Figure 8-25 Damage Index Versus Average Break Rate for Post-Earthquake System Performance Evaluation

Based on these results, the damage model used in this earthquake loss estimation methodology 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 8-25 as the NIBS curve. From this function, given knowledge of the pipe classification and length, one can estimate the system performance. That is, damage models 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.

8.1.7.1 Water System Performance Example

Assume a pipeline network of total length equal to 500 kilometers, 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 8-13. Note that the repair rates (R.R.) in this table are computed based on the equations provided in Section 8.1.6.5.

Table 8-13 Example of Water System Performance Evaluation

PGV (cm/sec)	R.R. (Repairs/ km)	Length (km)	# Repairs	PGD (in.)	Probab. of Liq.	R.R. (Repairs/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	1.0	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% * 43 = 34, and the estimated number of breaks is 9, while due to PGD, the estimated number of leaks is 20% * 89 = 18 and the estimated number of breaks is 71.

To apply the "conjugate" lognormal damage function, which has a median of 0.1 repairs/km and a beta of 0.85, the average break rate must first be computed:

- 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%

8.2 Wastewater Systems

This section presents an earthquake loss estimation methodology for a wastewater system. 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.

The scope of this section includes development of methods for estimation of earthquake damage to a wastewater system given knowledge of components (i.e., underground sewers and interceptors, wastewater treatment plants, and lift stations), classification (i.e., for wastewater treatment plants small, medium, or large), and the hazards (i.e., peak ground velocity, peak ground acceleration, and/or permanent ground deformation). Damage states describing the level of damage to each of the wastewater system components are defined (i.e., None, Slight, Moderate, Extensive, or Complete for facilities plus repair rates for sewers/interceptors). Fragility curves are developed for each classification of wastewater 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 wastewater system is presented.

8.2.1 Input Requirements and Output Information

Required input to estimate damage to wastewater systems is listed below.

- Sewers and Interceptors
    - Classification

  - Geographic location (polyline segments)
  - Peak ground velocity (PGV) and permanent ground deformation (PGD)
- Wastewater Treatment Plants and Lift Stations
  - Classification (small, medium, or large, with anchored or unanchored components)
  - Longitude and latitude of facility
  - Peak ground acceleration (PGA) and PGD

The baseline inventory data in Hazus includes an estimate of wastewater distribution pipeline length, aggregated at the Census tract level. 60% of the wastewater pipes are assumed to be brittle with the remaining pipes assumed to be ductile (see the *Hazus Inventory Technical Manual* for additional information on the baseline pipeline inventory data). In addition, peak ground velocity and permanent ground deformation (PGV and PGD) for each Census tract is needed for the analysis. The results from the distribution system analysis include the expected number of leaks and breaks per Census tract.

Other direct damage output for wastewater 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 wastewater system components are presented in Section 11.

8.2.2 Form of Damage Functions

Damage functions or fragility curves for wastewater 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.

8.2.3 Description of Wastewater System Components

As mentioned above, a wastewater 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 normally carry 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 manufactured with integral bell and spigot ends. 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: Lift stations are important parts of the wastewater 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. Lift stations are classified as either small (capacity less than 10 mgd), medium (capacity 10 – 50 mgd), or large (capacity greater than 50 mgd). Lift stations are also classified as having either anchored or unanchored subcomponents.

Wastewater Treatment Plants: 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). Wastewater treatment plants have the same processes as water treatment plants, with the addition of secondary treatment subcomponents.

8.2.4 Definitions of Damage States

Wastewater systems are susceptible to earthquake damage. Facilities such as wastewater treatment plants and lift stations are mostly vulnerable to PGA, and sometimes PGD, if located in liquefiable areas 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 models for these components are associated with those two hazard parameters.

8.2.4.1 Damage States Definitions for Components other than Sewers/Interceptors

A total of five damage states are defined for wastewater system components other than sewers and interceptors (i.e., lift stations and wastewater treatment plants). These are None, Slight, Moderate, Extensive, and Complete. For all damage states, wastewater facility damage is defined similarly to the equivalent water facility type (see Section 8.1.4.1), as follows:

- For wastewater treatment plants, all damage states are defined similarly to those for water treatment plants.
- For lift stations, all damage states are defined similarly to those for water pumping plants.

8.2.4.2 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 a leak, caused by joint pullout or crushing at the bell. In the Hazus 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.

8.2.5 Component Restoration Curves

The restoration curves for wastewater system components are based on ATC-13 (ATC, 1985) expert data (SF-31.a through SF-331.c). Normally distributed functions are used to approximate these restoration curves, as was done for transportation systems, and for potable water systems. Restoration functions are given in Table 8-14. The restoration functions are shown in Figure 8-26 and Figure 8-27. Figure 8-26 represents the restoration functions for lift stations and Figure 8-27 represents the restoration curves for wastewater treatment plants. For communication purposes, discretized restoration functions are provided in Table 8-15, where the restoration percentage is shown at discretized times. Although not directly used in Hazus, the discretized restoration functions are presented here as guidance. Restoration for sewers follows the same approach for potable water pipelines, presented in Section 8.1.5.

Table 8-14 Restoration Functions for Wastewater System Components (All Normal Distributions)

Classification	Damage State	Mean (days)	σ (days)
Lift Stations	Slight	1.3	0.7
	Moderate	3.0	1.5
	Extensive	21.0	12.0
	Complete	65.0	25.0
Wastewater Treatment Plants	Slight	1.5	1.0
	Moderate	3.6	2.5
	Extensive	55.0	25.0
	Complete	160.0	60.0

Table 8-15 Discretized Restoration Functions for Wastewater System Components

Classification	Damage State	Functional Percentage				
		1 day	3 days	7 days	30 days	90 days
Lift Stations	Slight	34	100	100	100	100
	Moderate	10	50	100	100	100
	Extensive	5	7	13	78	100
	Complete	0	1	2	9	85
Wastewater Treatment Plants	Slight	31	94	100	100	100
	Moderate	15	40	92	100	100
	Extensive	2	2	3	16	92
	Complete	1	1	1	2	13

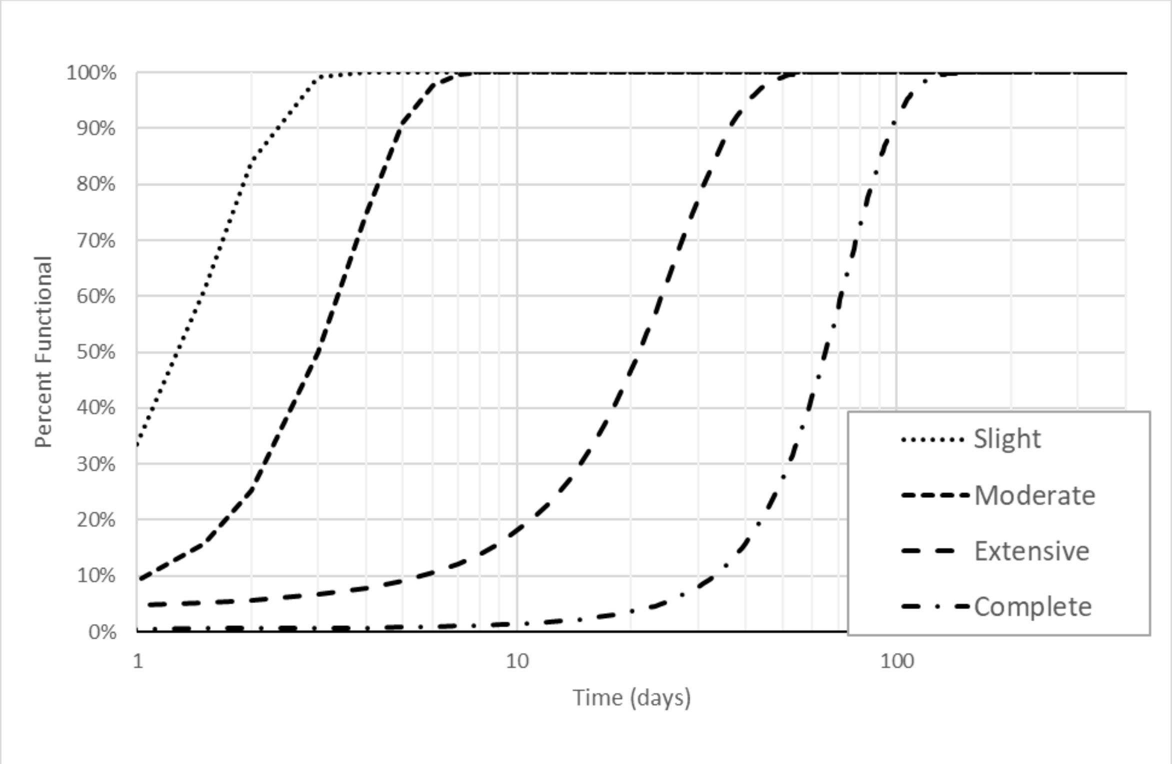


Figure 8-26 Restoration Curves for Lift Stations

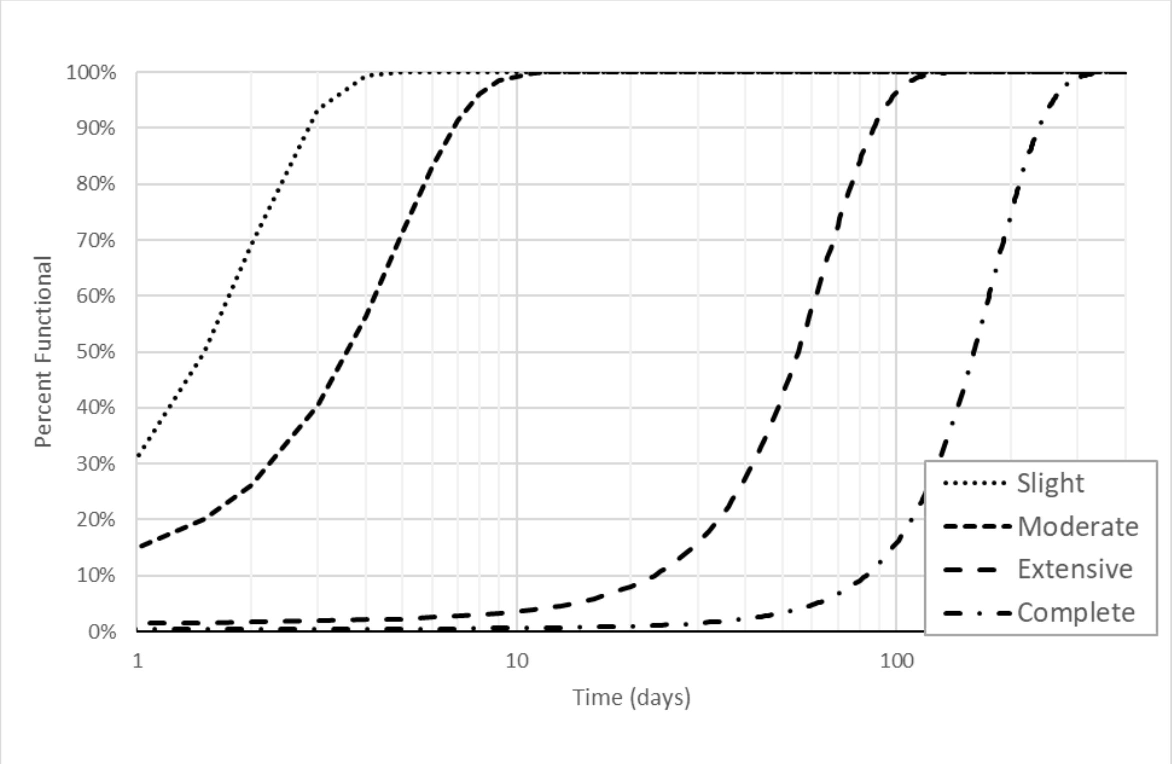


Figure 8-27 Restoration Curves for Wastewater Treatment Plants

8.2.6 Development of Damage Functions

In this subsection, damage functions for the various components of a wastewater system are presented. In cases where the components are made of subcomponents (i.e., wastewater 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. Further information on the wastewater system facility subcomponent fragilities can be found in Appendix B.

Damage functions due to ground failure (i.e., PGD) for wastewater treatment plants and lift stations are assumed to be similar to those described for potable water system facilities in Section 8.1.4.1.

8.2.6.1 Damage Functions for Life Stations and Wastewater Treatment Plants

Damage functions for lift stations are similar to those of pumping plants in potable water systems described in Section 8.1.4.1. Table 8-16, Table 8-17, and Table 8-18 present damage functions for small, medium, and large wastewater treatment plants, respectively. Figure 8-28 through Figure 8-33 present the fragility curves for the different classes of wastewater treatment plants. Damage functions available within Hazus are the functions for facilities with unanchored components. User's wishing to analyze facilities with anchored components can revise the existing damage functions through the Hazus menus.

Table 8-16 Peak Ground Acceleration Fragility Functions for Small Wastewater Treatment Plants

Classification	Damage State	Median (g)	β
Small Wastewater Treatment Plants (WWTS) with anchored components	Slight	0.23	0.40
	Moderate	0.35	0.40
	Extensive	0.48	0.50
	Complete	0.80	0.55
Small Wastewater Treatment Plants (WWTS) with unanchored components (WWT2)	Slight	0.16	0.40
	Moderate	0.26	0.40
	Extensive	0.48	0.50
	Complete	0.80	0.55

Table 8-17 Peak Ground Acceleration Fragility Functions for Medium Wastewater Treatment Plants

Classification	Damage State	Median (g)	β
Medium Wastewater Treatment Plants (WWTM) with anchored components	Slight	0.33	0.40
	Moderate	0.49	0.40
	Extensive	0.70	0.45
	Complete	1.23	0.55
Medium Wastewater Treatment Plants (WWTM) with unanchored components	Slight	0.20	0.40
	Moderate	0.33	0.40
	Extensive	0.70	0.45
	Complete	1.23	0.55

Table 8-18 Peak Ground Acceleration Fragility Functions for Large Wastewater Treatment Plants

Classification	Damage State	Median (g)	β
Large Wastewater Treatment Plants (WWTL) with anchored components	Slight	0.40	0.40
	Moderate	0.56	0.40
	Extensive	0.84	0.40
	Complete	1.50	0.40
Large Wastewater Treatment Plants (WWTL) with unanchored components	Slight	0.22	0.40
	Moderate	0.35	0.40
	Extensive	0.84	0.40
	Complete	1.50	0.40

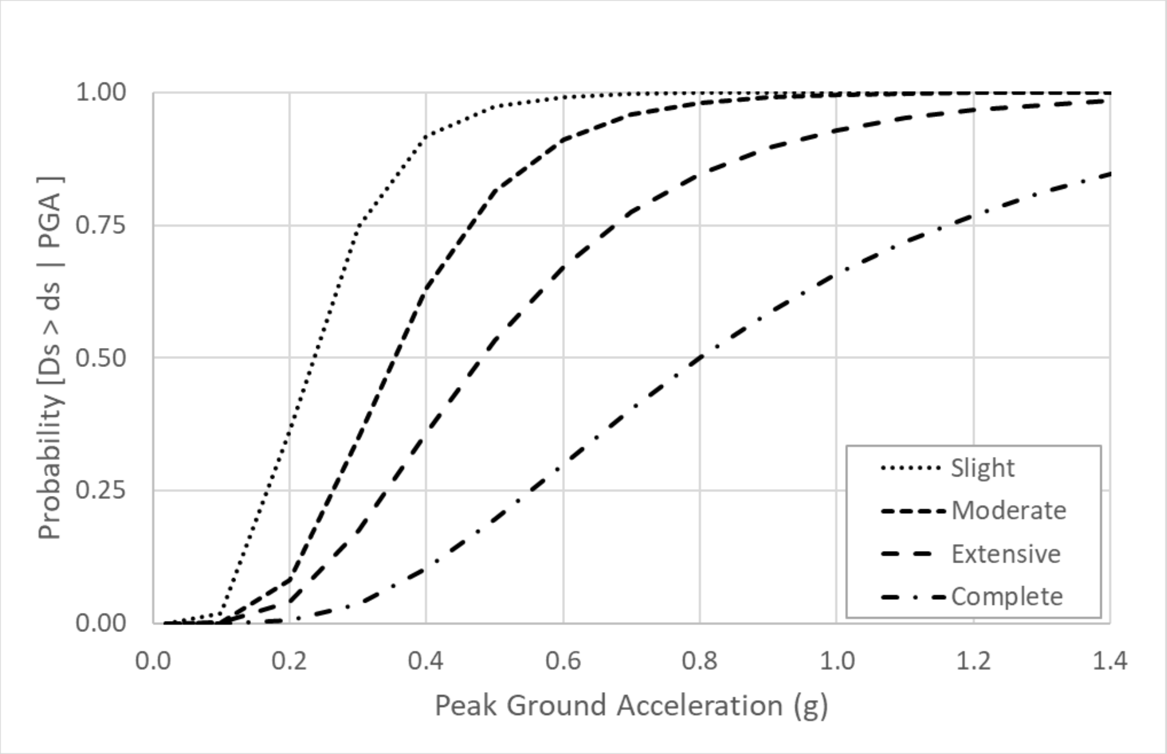


Figure 8-28 Fragility Functions for Small Wastewater Treatment Plants with Anchored

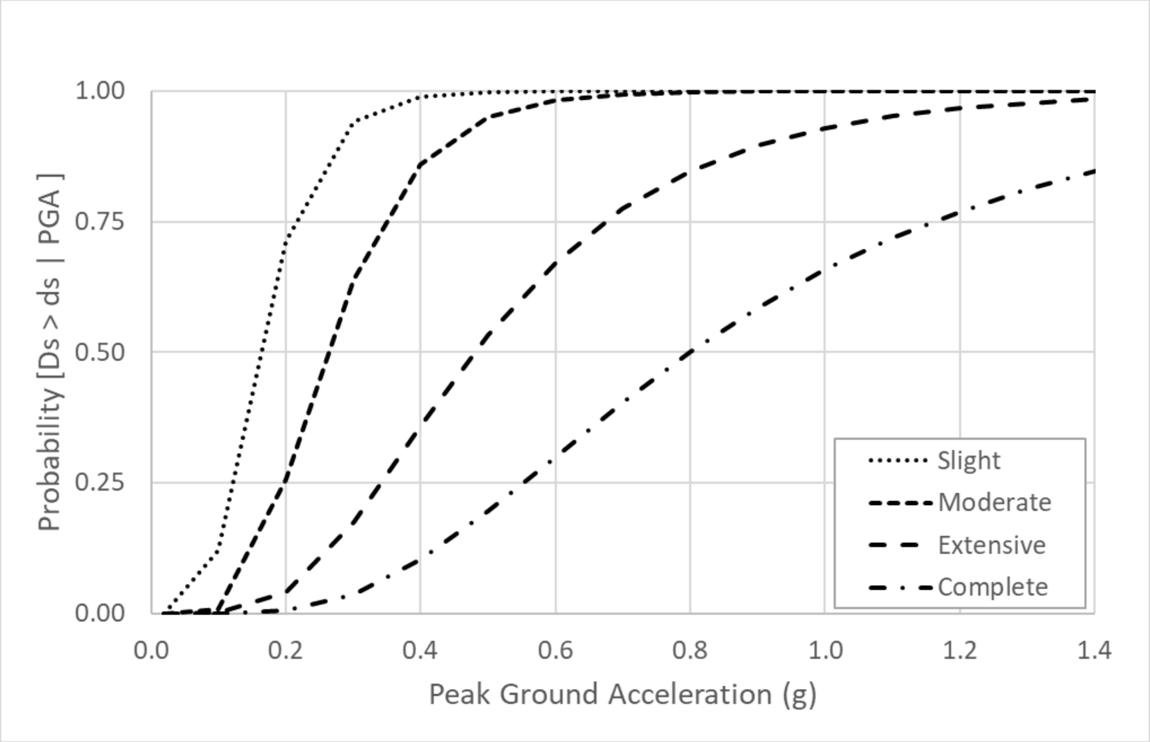


Figure 8-29 Fragility Functions for Small Wastewater Treatment Plants with Unanchored Components

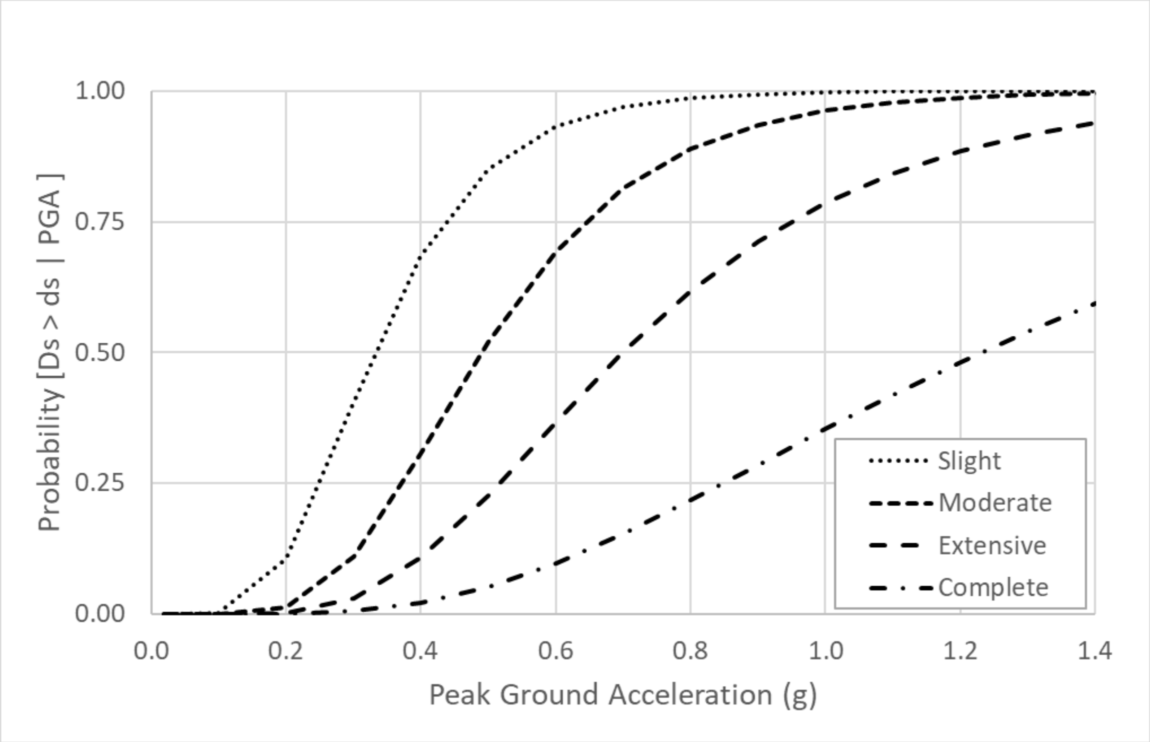


Figure 8-30 Fragility Functions for Medium Wastewater Treatment Plants with Anchored Components

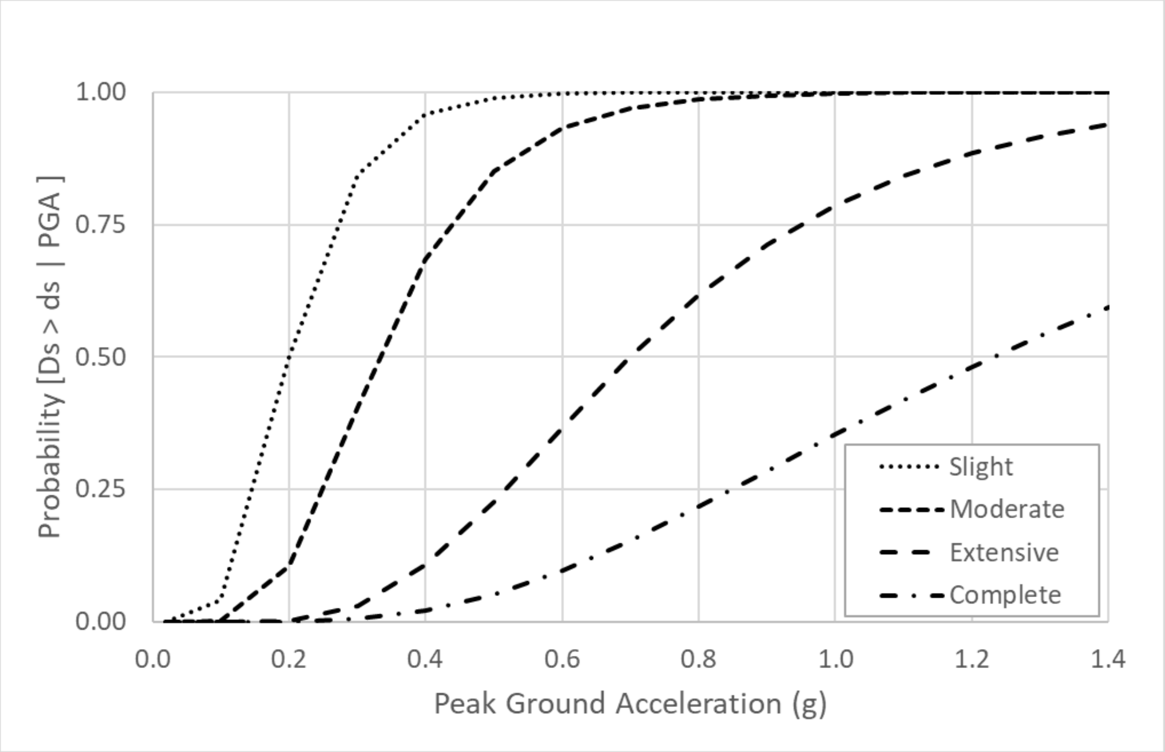


Figure 8-31 Fragility Functions for Medium Wastewater Treatment Plants with Unanchored Components

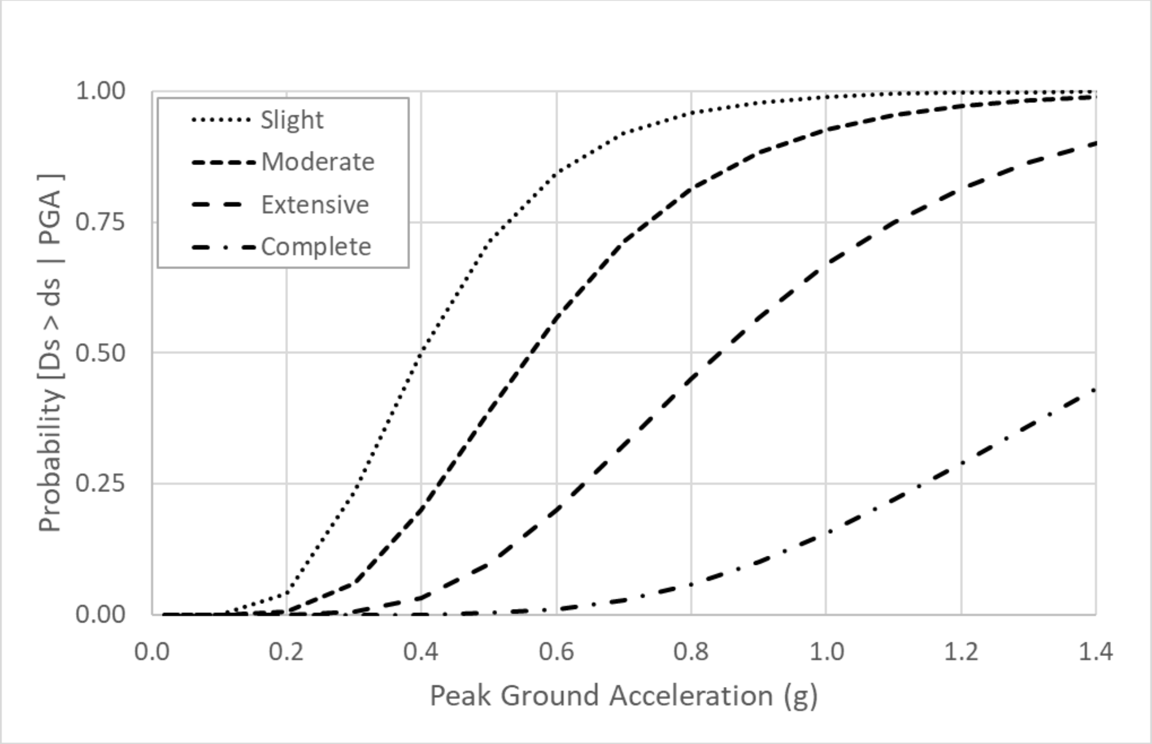


Figure 8-32 Fragility Functions for Large Wastewater Treatment Plants with Anchored Components

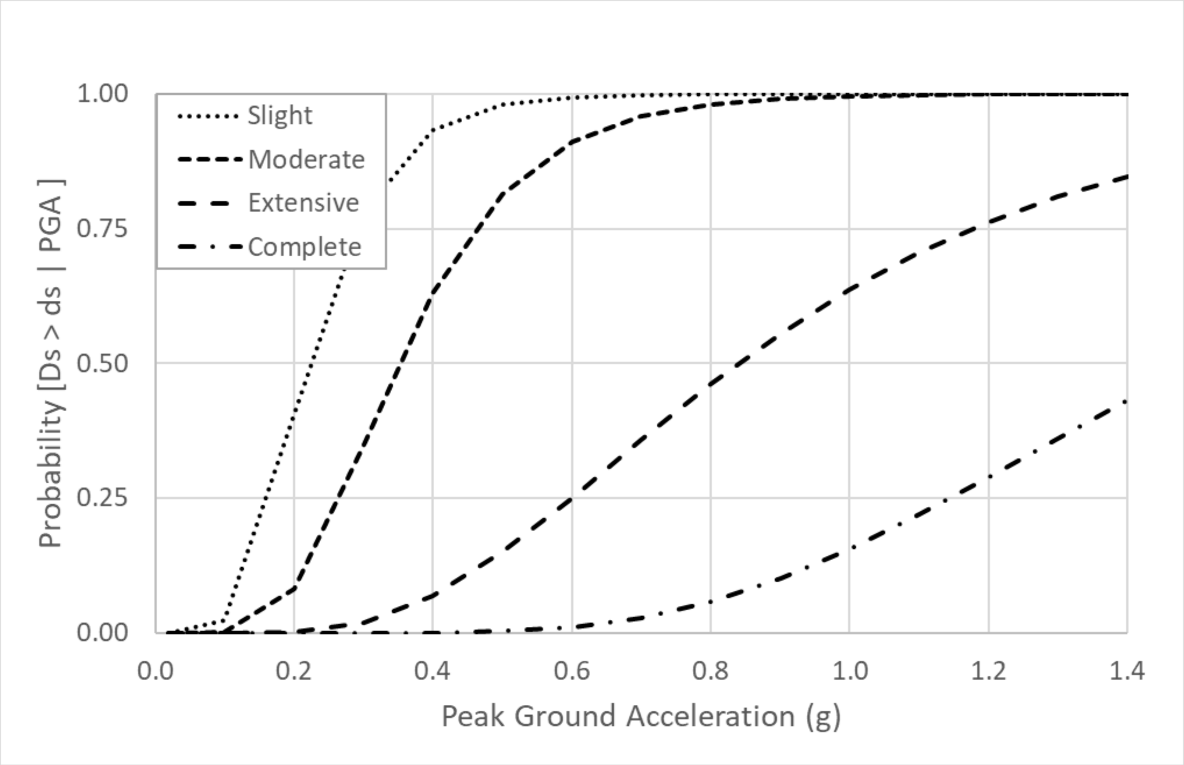


Figure 8-33 Fragility Functions for Large Wastewater Treatment Plants with Unanchored Components

8.2.6.2 Damage Functions for Sewers and Interceptors

The same damage models proposed for buried pipelines in potable water systems (Section 8.1.6.5) are assumed to apply to sewers and interceptors. These are listed again in Table 8-19, where R.R. is the repair rate or number of repairs per kilometer, PGV is peak ground velocity in cm/sec, and PGD is permanent ground deformation in inches.

Table 8-19 Damage Models for Sewers/Interceptors

Pipe Type	PGV Model		PGD Model	
	R. R. $\cong$ 0.0001 * PGV$^{(2.25)}$		R. R. $\cong$ Prob[liq] * PGD$^{(0.56)}$	
	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

8.3 Oil Systems

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

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 hazards (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. None, Slight, Moderate, Extensive or Complete, plus repair rates for pipelines). Fragility curves are developed for each classification of the oil system components. 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 oil system is presented.

8.3.1 Input Requirements and Output Information

Required input to estimate damage to oil system components is listed below.

Refineries, Pumping Plants, and Tank Farms

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

Oil Pipelines

- Classification
- Geographical location (polyline segments)
- PGV and PGD

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 11.

While there is no baseline data for oil pipelines, users may import their own pipeline data for analysis. The pipeline damage results would include the expected number of leaks and breaks.

8.3.2 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 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.

8.3.3 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: Refineries are an important part of an oil system. They process crude oil before it can be used. Although the supply of water is critical to the functioning of a 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 and Large refineries (capacity of 100,000 to 500,000 barrels per day and more than 500,000 barrels per day, respectively) 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 crude oil over long distances. About 75% 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. Buried pipelines are considered to be vulnerable to PGV and PGD.

Pumping Plants: 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 Section 7.2.3.

Tank Farms: Tank farms are facilities that store fuel products. They include tanks, pipes, and electrical components. Tank farms are classified as having either anchored or unanchored subcomponents, as defined in Section 7.2.3.

8.3.4 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 areas or landslide zones. Therefore, the damage states for these components are defined and associated with PGA and PGD. In contrast, pipelines are vulnerable to PGV and PGD.

8.3.4.1 Damage States Definitions for Components other than Pipelines

A total of five damage states are defined for oil system components other than pipelines, i.e. refineries, pumping plants and tank farms. These are None, Slight, Moderate, Extensive, and Complete.

Slight Damage

- For refineries, Slight damage is defined by malfunction of the plant for a short time (a few days) due to loss of electric power and backup power, if any, or light damage to the tanks.
- For pumping plants, Slight damage is defined by Slight damage to the building. At this level of damage, performance of the facility is governed by the performance of the building.
- For tank farms, Slight damage is defined by malfunction of the plant for a short time (less than three days) due to loss of backup power or light damage to the tanks.

Moderate Damage

- For refineries, Moderate damage 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 the tanks.
- For pumping plants, Moderate damage is defined by considerable damage to mechanical and electrical equipment, or considerable damage to the building.
- For tank farms, Moderate damage is defined by malfunction of the 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

- For refineries, Extensive damage is defined by the tanks being extensively damaged, or the stacks collapsing.
- For pumping plants, Extensive damage is defined by the building being extensively damaged, or the pumps being badly damaged.
- For tank farms, Extensive damage is defined by the tanks being extensively damaged, or extensive damage to elevated pipes.

Complete Damage

- For refineries, Complete damage is defined by the complete failure of all elevated pipes or collapse of tanks.
- For pumping plants, Complete damage is defined by the building being in the complete damage state; at this level of damage, the performance of the building governs the facility's overall damage state.
- For tank farms, Complete damage is defined by the complete failure of all elevated pipes or collapse of tanks.

8.3.4.2 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 wall. In the Hazus 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.

8.3.5 Component Restoration Curves

The restoration curves for oil system components are obtained using the data for mean restoration time from ATC-13 (ATC, 1985). The restoration functions for pumping plants are similar to those of pumping plants in the potable water system (see Section 8.1.5). 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 8-20. Figure 8-34 presents the restoration functions for refineries, and Figure 8-35 provides the restoration curves for tank farms. The discretized restoration functions are presented in Table 8-21, where the restoration percentage is given at discretized times. Although not directly used in Hazus, the discretized restoration functions are presented here as guidance. Restoration for oil pipelines follows the same approach for potable water pipelines, presented in Section 8.1.5.

Table 8-20 Restoration Functions for Oil System Components (All Normal Distributions)

Classification	Damage State	Mean (days)	σ (days)
Refineries	Slight	0.4	0.1
	Moderate	3.0	2.2
	Extensive	14.0	12.0
	Complete	190.0	80.0
Tank Farms	Slight	0.9	0.5
	Moderate	7.0	7.0
	Extensive	28.0	26.0
	Complete	70.0	55.0

Table 8-21 Discretized Restoration Functions for Oil System Components

Classification	Damage State	Functional Percentage				
		1 day	3 days	7 days	30 days	90 days
Refineries	Slight	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	58	100	100	100	100
	Moderate	7.0	29	50	100	100
	Extensive	28.0	17	21	54	100

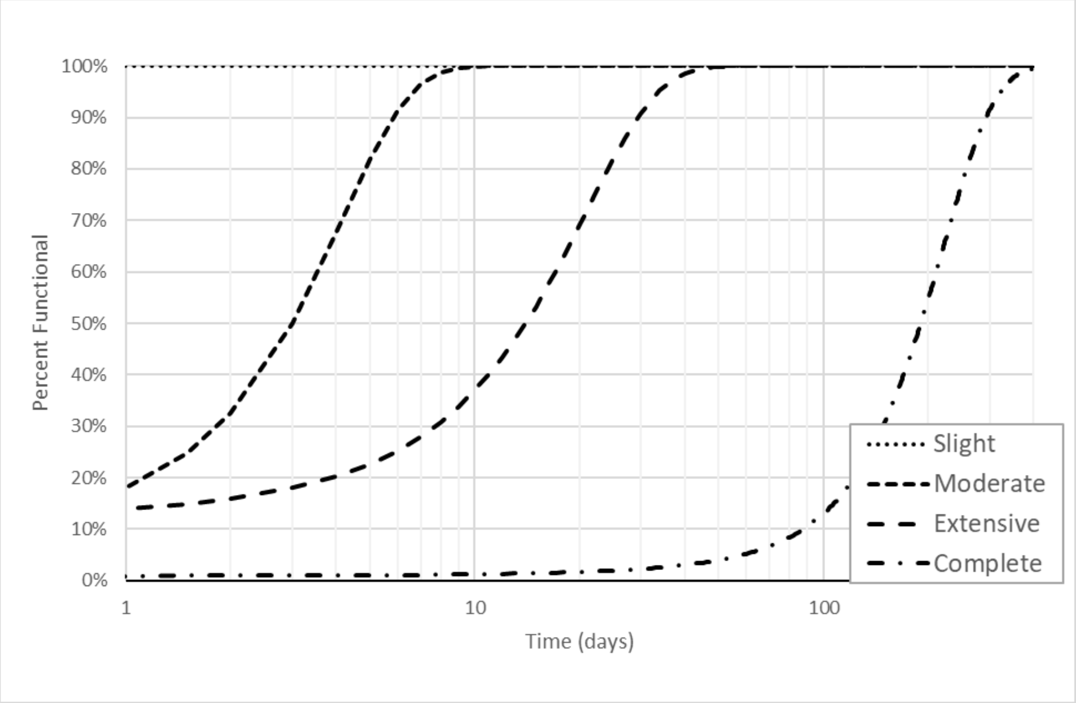


Figure 8-34 Restoration Curves for Refineries

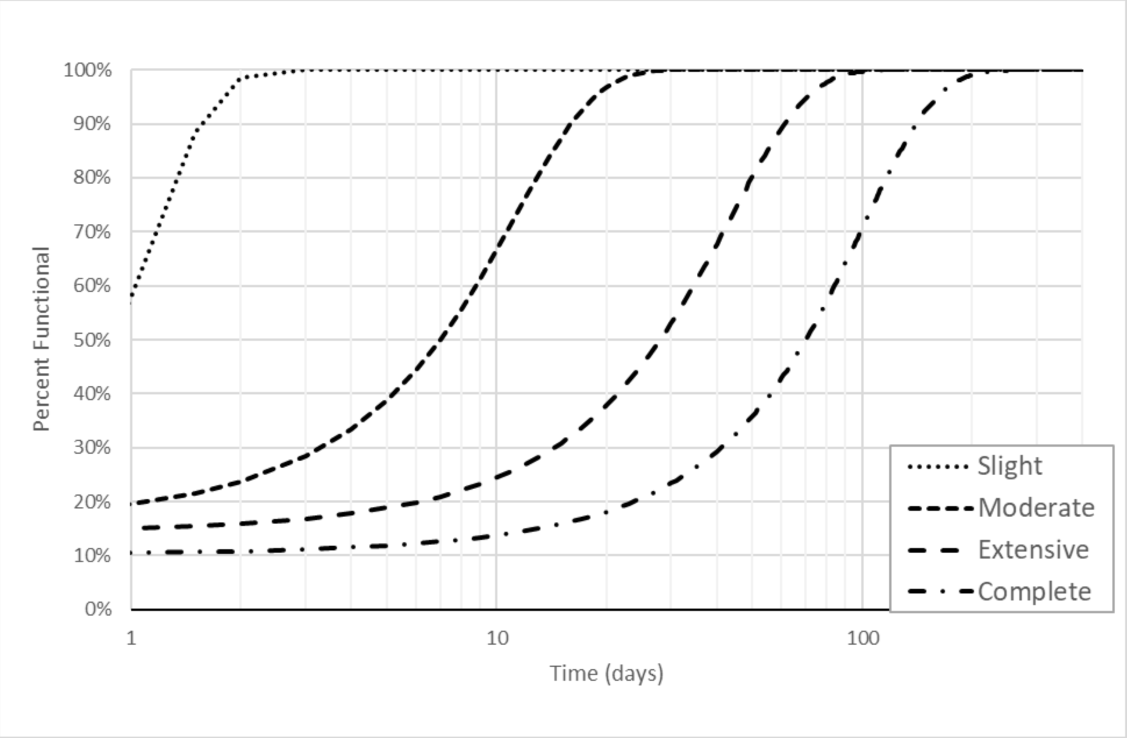


Figure 8-35 Restoration Curves for Tank Farms

8.3.6 Development of Damage Functions

In this subsection, damage functions for the various components of an 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. Further information on the oil system facility subcomponent fragilities can be found in Appendix B.

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 8.1.6.

8.3.6.1 Damage Functions for Refineries

Ground shaking-related damage functions for refineries are developed with respect to facility classification. Table 8-22 and Table 8-23 present damage functions for small and medium/large refineries, respectively. These fragility curves are also plotted in Figure 8-36 through Figure 8-39. Damage functions available within Hazus are the functions for facilities with unanchored components. User's wishing to analyze facilities with anchored components could revise the existing damage functions through the Hazus menus.

Table 8-22 Peak Ground Acceleration Fragility Functions for Small Refineries (Capacity < 100,000 barrels/day)

Classification	Damage State	Median (g)	σ
Refineries with anchored components (ORF1)	Slight	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	0.13	0.50
	Moderate	0.27	0.50
	Extensive	0.43	0.60
	Complete	0.68	0.55

Table 8-23 Peak Ground Acceleration Fragility Functions for Medium/Large Refineries (Capacity * 100,000 barrels/day)

Classification	Damage State	Median (g)	σ
Refineries with anchored components (ORF3)	Slight	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	0.17	0.40
	Moderate	0.32	0.45
	Extensive	0.68	0.50
	Complete	1.04	0.45

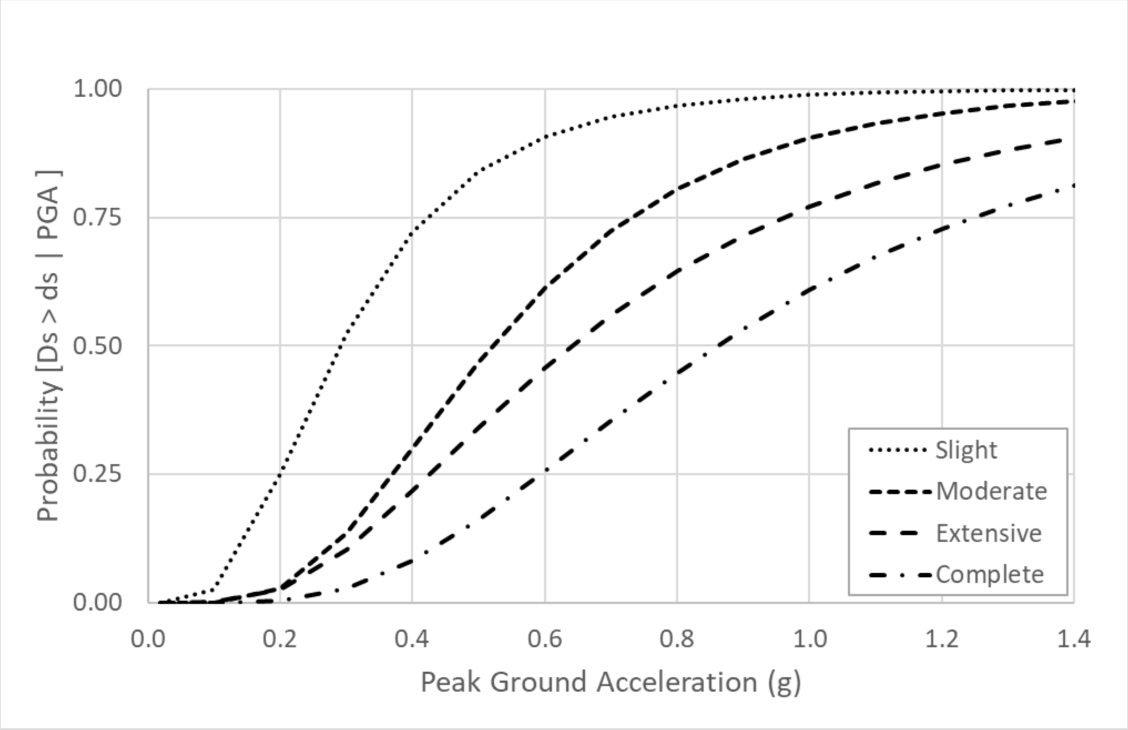


Figure 8-36 Fragility Curves for Small Refineries with Anchored Components

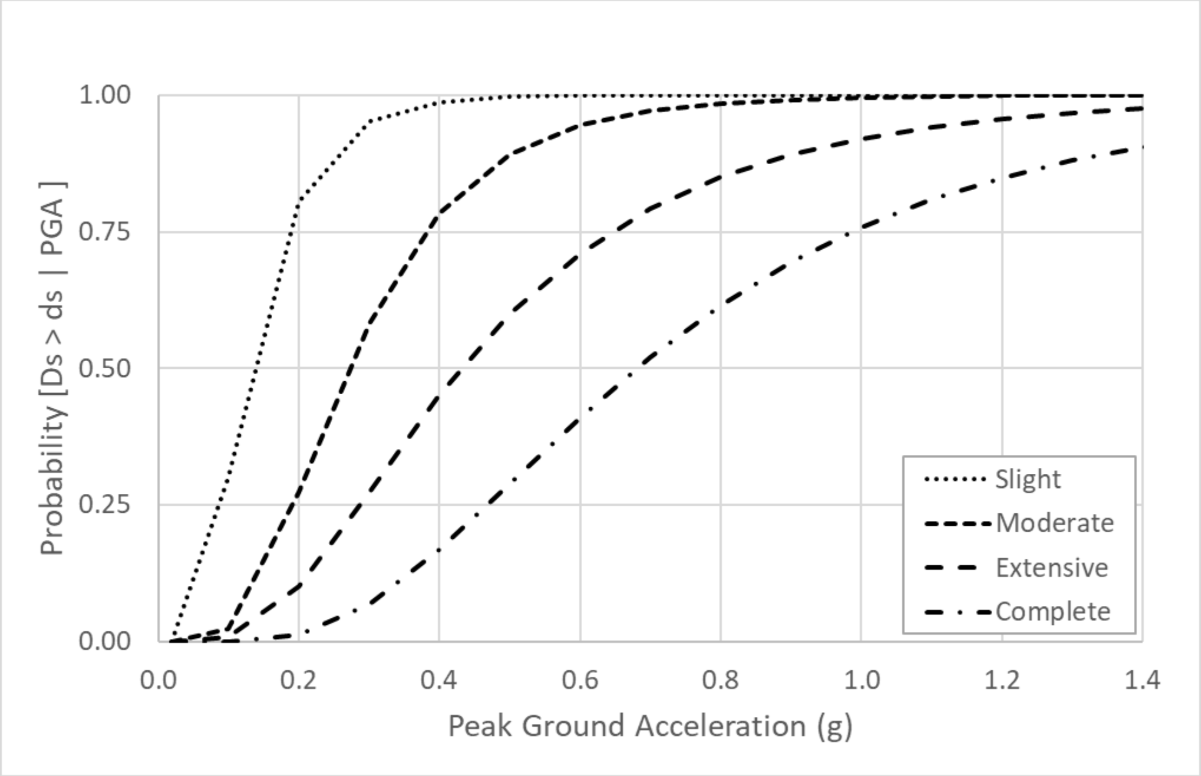


Figure 8-37 Fragility Curves for Small Refineries with Unanchored Components

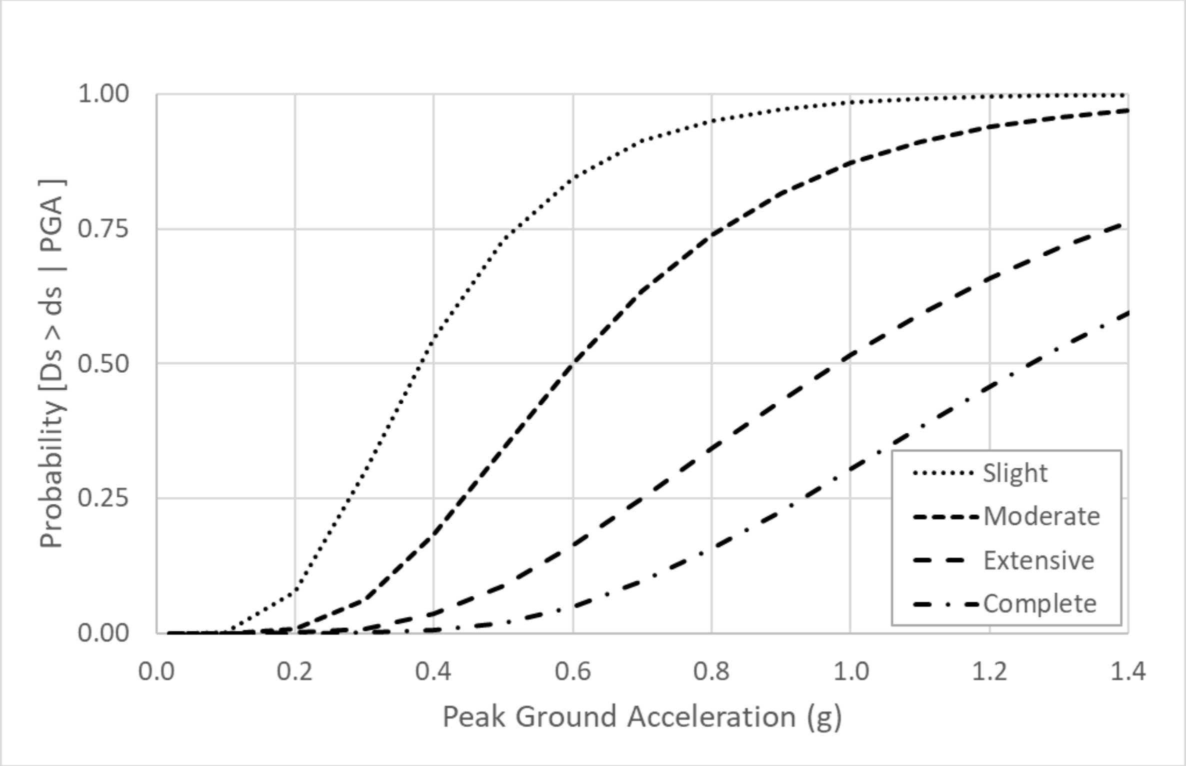


Figure 8-38 Fragility Curves for Medium/Large Refineries with Anchored Components

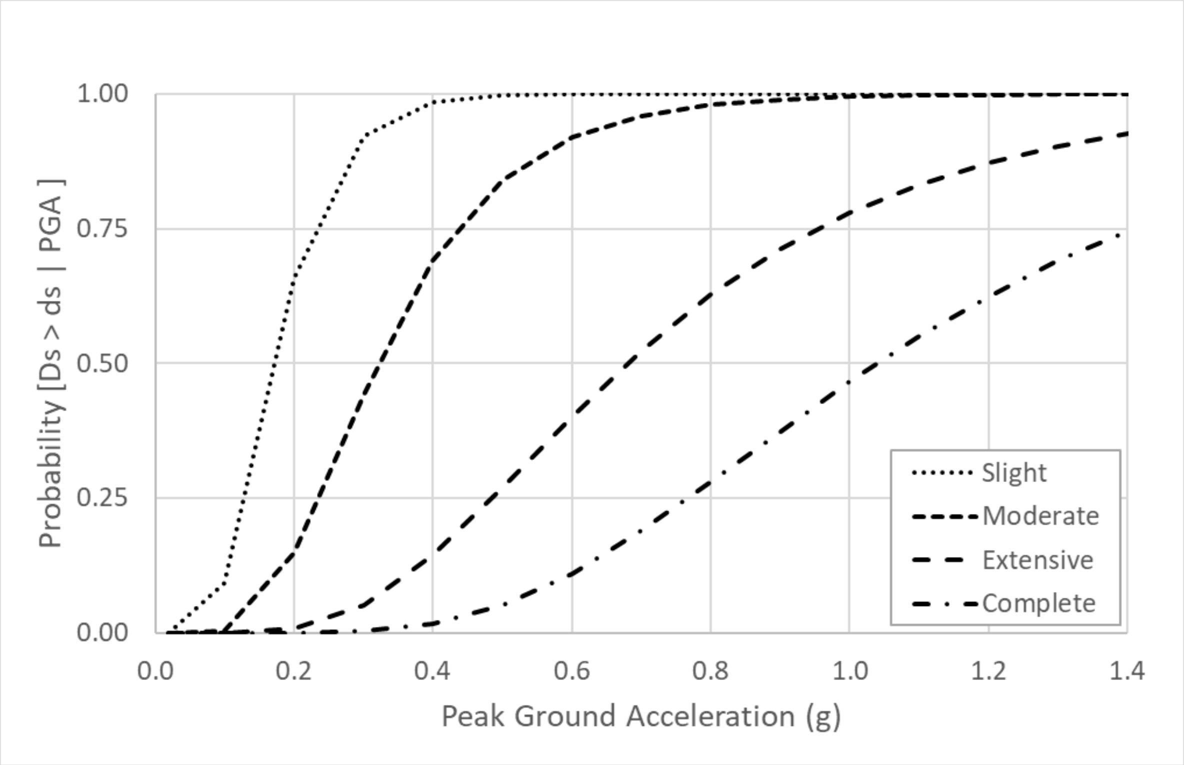


Figure 8-39 Fragility Curves for Medium/Large Refineries with Unanchored Components

8.3.6.2 Damage Functions for Pumping Plants

Ground shaking-related damage functions for pumping plants are also developed with respect to classification and ground motion parameter and are presented in Table 8-24. These damage functions are plotted in Figure 8-40 and Figure 8-41. Damage functions available within Hazus are the functions for facilities with unanchored components. User's wishing to analyze facilities with anchored components can revise the existing damage functions through the Hazus menus.

Table 8-24 Peak Ground Acceleration Fragility Functions for Pumping Plants

Classification	Damage State	Median (g)	σ
Pumping Plants (OPP) with anchored components	Slight	0.15	0.75
	Moderate	0.34	0.65
	Extensive	0.77	0.65
	Complete	1.50	0.80
Pumping Plants (OPP) with unanchored components	Slight	0.12	0.60
	Moderate	0.24	0.60
	Extensive	0.77	0.65
	Complete	1.50	0.80

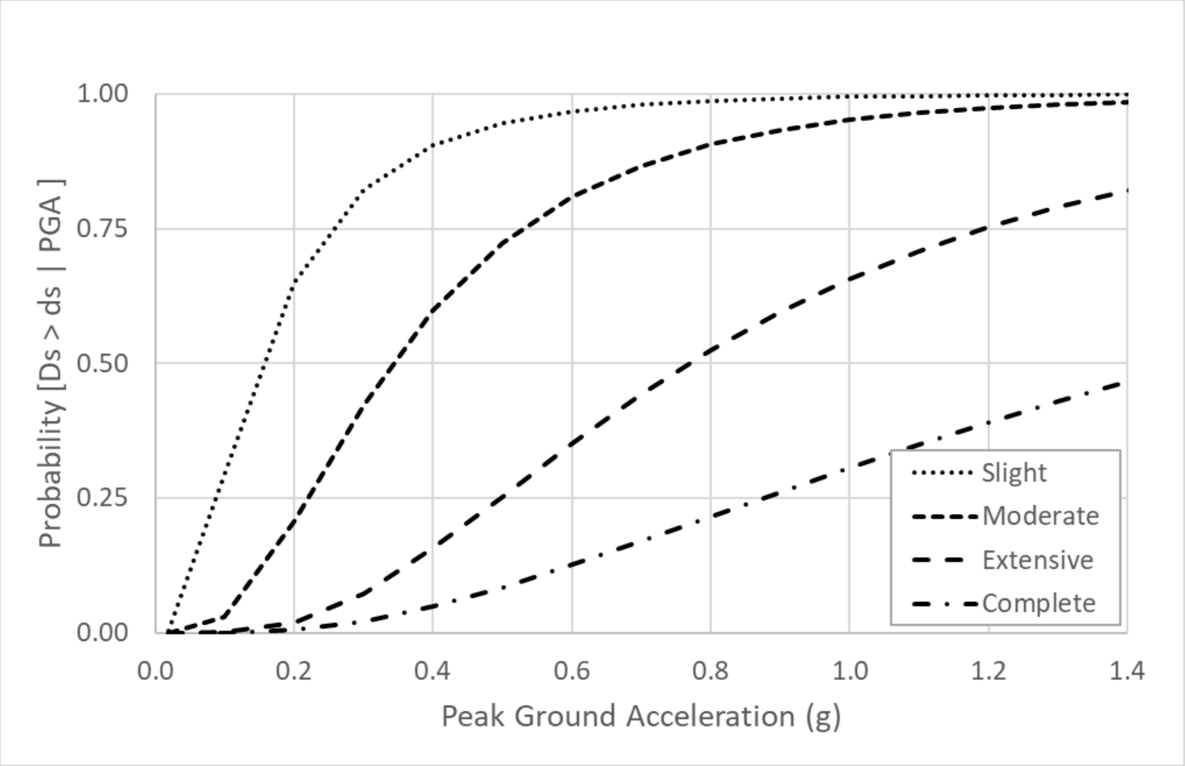


Figure 8-40 Fragility Curves for Pumping Plants with Anchored Components

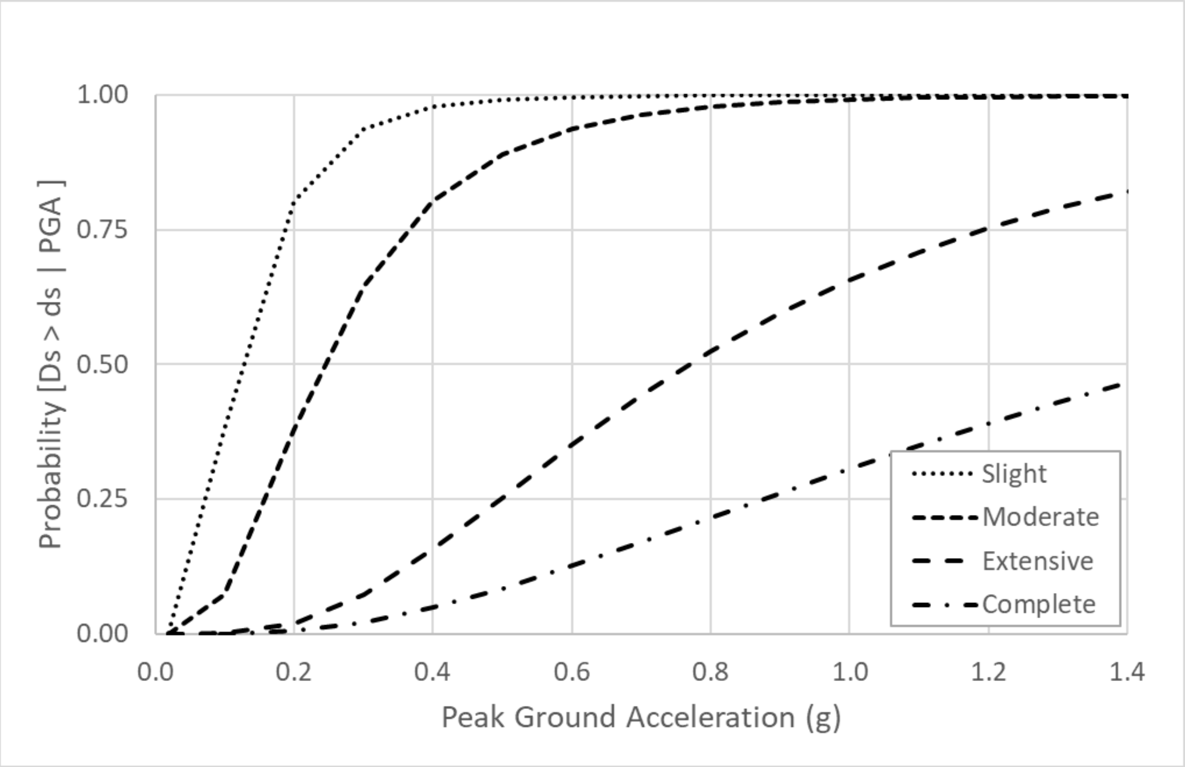


Figure 8-41 Fragility Curves for Pumping Plants with Unanchored Components

8.3.6.3 Damage Functions for Tank Farms

Ground shaking-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 8-25. The fragility curves are plotted in Figure 8-42 and Figure 8-43. Damage functions available within Hazus are the functions for facilities with unanchored components. User's wishing to analyze facilities with anchored components can revise the existing damage functions through the Hazus menus.

Table 8-25 Peak Ground Acceleration Fragility Functions for Tank Farms

Classification	Damage State	Median (g)	σ
Plants with anchored components (OTF1)	Slight	0.29	0.55
	Moderate/Extensive	0.50	0.55
	Complete	0.87	0.50
Plants with unanchored components (OTF2)	Slight	0.12	0.55
	Moderate	0.23	0.55
	Extensive	0.41	0.55
	Complete	0.68	0.55

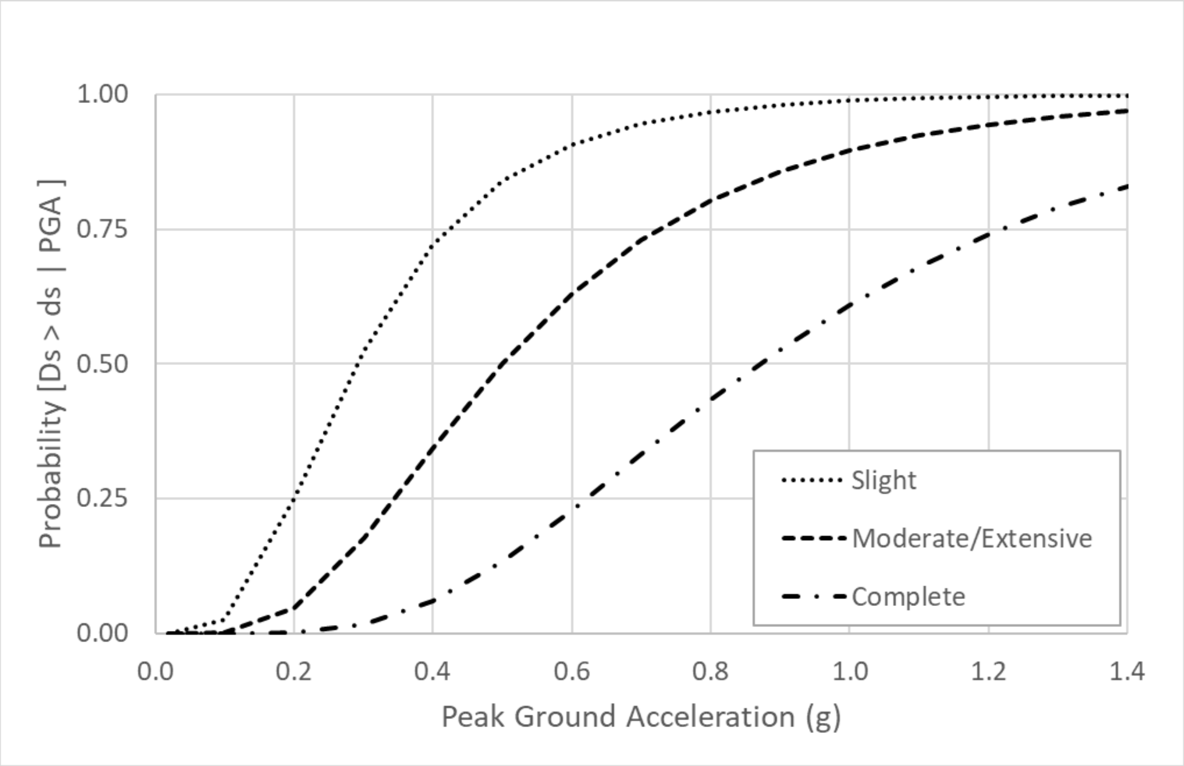


Figure 8-42 Fragility Curves for Tank Farms with Anchored Components

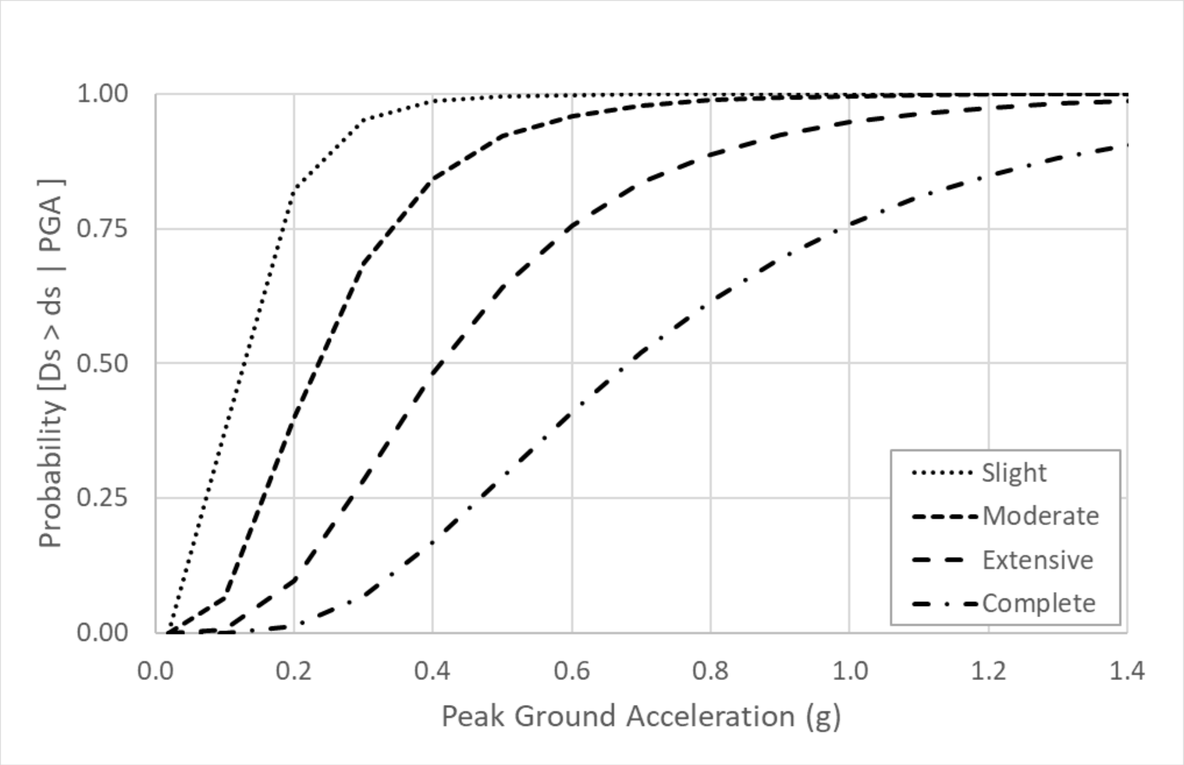


Figure 8-43 Fragility Curves for Tank Farms with Unanchored Components

8.3.6.4 Damage Functions for Oil Pipelines

The same two damage models proposed for potable water pipelines (see Section 8.1.6.5) are assumed to apply to crude and refined oil pipelines (Table 8-26). Note that mild steel pipelines with submerged arc welded joints are classified as ductile pipes, while the older gas welded steel pipelines, if any, are classified as brittle pipes. The damage models are provided in Table 8-26, where R.R. is the repair rate or number of repairs per kilometer, PGV is peak ground velocity in cm/sec, and PGD is permanent ground deformation in inches.

Table 8-26 Damage Models for Oil Pipelines

Pipe Type	PGV Model		PGD Model	
	R. R. ≅ 0.0001 * PGV$^{(2.25)}$		R. R. ≅ Prob[liq] * PGD$^{(0.56)}$	
	Multiplier	Example of Pipe	Multiplier	Example of Pipe
Brittle Oil Pipelines (OIP1)	1	Steel Pipe w/ Gas welded joints	1	Steel Pipe w/ Gas welded joints
Ductile Oil Pipelines (OIP2)	0.3	Steel Pipe w/ Arc welded joints	0.3	Steel Pipe w/ Arc welded joints

8.4 Natural Gas Systems

A natural gas system consists of compressor stations and buried 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.

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 the hazards (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., None, Slight, 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.

8.4.1 Input Requirements and Output Information

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

- Compressor Stations
    - Classification (with anchored or unanchored components)
    - Geographic location of facility (longitude and latitude)
    - Peak ground acceleration (PGA) and permanent ground deformation (PGD)
- Natural Gas Pipelines
    - Classification
    - Geographic location (polyline segments)
    - Peak ground velocity (PGV) and PGD

The baseline inventory data in Hazus includes an estimate of natural gas distribution pipeline length, aggregated at the Census tract level. 10% of the pipes are assumed to be brittle with the remaining pipes assumed to be ductile (see the *Hazus Inventory Technical Manual* for additional information on the baseline pipeline inventory data). In addition, peak ground velocity and permanent ground deformation (PGV and PGD) for each Census tract is needed for the analysis. The results from the distribution system analysis include the expected number of leaks and breaks per Census tract.

Other 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 11.

8.4.2 Form of Damage Functions

Damage functions or fragility curves for natural gas 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 natural gas 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 these fragility curves are presented in the next section.

8.4.3 Description of Natural Gas System Components

A natural gas system typically consists of compressor stations and pipelines, as defined below:

Compressor Stations: Compressor stations serve to maintain the flow of gas in 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. The compressor stations are similar to pumping plants in oil systems discussed in Section 8.3.3.

Natural Gas Pipelines: Natural gas 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.

8.4.4 Definitions of Damage States

Facilities such as compressor stations are mostly vulnerable to PGA, and sometimes PGD, if located in liquefiable areas 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 hazard parameters.

A total of five damage states are defined for compressor stations. These are None, Slight, Moderate, Extensive, and Complete.

- Slight damage is defined by slight damage to the building; at this level of damage, the performance of the building governs the facility's overall damage state.
- Moderate damage is defined by considerable damage to mechanical and electrical equipment, or considerable damage to the building.
- Extensive damage is defined by the building being extensively damaged, or the pumps being badly damaged beyond repair.
- Complete damage is defined by the building being in the Complete damage state; at this level of damage, the performance of the building again governs the facility's overall damage state.

For pipelines, two damage states are considered: 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.

8.4.5 Component Restoration Curves

The restoration curves for natural gas system components are similar to those of the oil system discussed in 8.3.5, which in turn, are similar to those of potable water systems (Section 8.1.5).

8.4.6 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 are taken as identical to those of pumping plants in oil systems discussed in Section 8.3.6.2. Damage functions for natural gas pipelines are taken as identical to those for oil pipelines discussed in Section 8.3.6.4.

8.5 Electric Power Systems

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.

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 hazards (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., None, Slight, Moderate, Extensive or Complete). Fragility curves are developed for each classification of electric power system components. These curves describe the probability of reaching or exceeding each damage state given the level of ground motion.

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

8.5.1 Input Requirements and Output Information

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

- Substations
  - Classification (low, medium, or high voltage; with anchored or unanchored/standard components)
  - Longitude and latitude of facility
  - PGA and PGD
- Distribution Circuits
  - Classification (seismically designed or standard components)
  - Geographic location (polyline segments)
  - PGA
- Generation Plants
  - Classification (small, medium, or large, with anchored or unanchored components)
  - Longitude and latitude of facility
  - PGA

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. Note that damage ratios for each of the electric power system components are presented in Section 11. A simplified power system performance evaluation methodology is also provided. The output from this simplified version of a system analysis consists of a probabilistic estimate for the power outage (i.e., the number of households without power). Details of this methodology are provided in Section 8.5.7.

8.5.2 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 (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)

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

8.5.3 Description of Electric Power System Components

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.

8.5.3.1 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 lightning 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 Large (500 kV) substations, Medium (230kV) substations, and Small (115kV) substations, respectively. The classification is also a function of whether the subcomponents are anchored or typical (unanchored), as defined in Section 7.2.3.

8.5.3.2 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.

8.5.3.3 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 (MW) of electric power that the plant can produce under normal operations. Small generation plants have a generation capacity of less than 100 MW. Medium generation plants have a capacity between 200 and 500 MW, while Large plants have a capacity greater than 500 MW. Fragility curves for generation plants with anchored versus unanchored subcomponents are presented.

8.5.4 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 area 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, Slight, Moderate, Extensive, and Complete.

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 n4 current transformers, the substation is said to be in a Slight 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 the 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, dispersions obtained from the small sample numbers along with the relatively constant median values are used.

Slight Damage

- For substations, Slight damage 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 the Slight damage state.

- For distribution circuits, Slight damage is defined by the failure of 4% of all circuits.
- For generation plants, Slight damage is defined by turbine tripping, light damage to the diesel generator, or by the building being in the Slight damage state.

Moderate Damage

- For substations, Moderate damage is defined as the failure of 40% of disconnect switches (e.g., misalignment), 40% of circuit breakers (e.g., circuit breaker phase sliding off its pad, circuit breaker tipping over, or interrupter-head falling to the ground), failure of 40% of current transformers (e.g., oil leaking from transformers, porcelain cracked), or by the building being in the Moderate damage state.
- For distribution circuits, Moderate damage is defined by the failure of 12% of circuits.
- For generation plants, Moderate damage is defined some by the chattering of instrument panels and racks, considerable damage to boilers and pressure vessels, or by the building being in the Moderate damage state.

Extensive Damage

- For substations, Extensive damage 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 the Extensive damage state.
- For distribution circuits, Extensive damage is defined by the failure of 50% of all circuits.
- For generation plants, Extensive damage is defined by considerable damage to motor driven pumps, or considerable damage to large vertical pumps, or by the building being in the Extensive damage state.

Complete Damage

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

8.5.5 Component Restoration Curves

Restoration curves for electric substations and distribution circuits are based on a G&E report (1994e), while restoration curves for generation facilities are obtained using the data for mean restoration times from ATC-13 (ATC, 1985) social function SF-29.a (the first four damage states). These functions are presented in Table 8-27 and Table 8-28. 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. Although not directly used in Hazus, the discretized restoration functions are presented here as guidance. The continuous restoration functions are also shown in Figure 8-44 through Figure 8-46.

Table 8-27 Restoration Functions for Electric Power System Components (All Normal Distributions)

Classification	Damage State	Median (days)	σ (days)
Electric Substations	Slight	1.0	0.5
	Moderate	3.0	1.5
	Extensive	7.0	3.5
	Complete	30.0	15.0
Distribution Circuits	Slight	0.3	0.2
	Moderate	1.0	0.5
	Extensive	3.0	1.5
	Complete	7.0	3.0
Generation Facilities	Slight	0.5	0.1
	Moderate	3.6	3.6
	Extensive	22.0	21.0
	Complete	65.0	30.0

Table 8-28 Discretized Restoration Functions for Electric Power Components

Classification	Damage State	Functional Percentage				
		1 day	3 days	7 days	30 days	90 days
Electric Substations	Slight	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	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	100	100	100	100	100
	Moderate	24	44	83	100	100
	Extensive	16	19	24	65	100
	Complete	2	2	3	13	80

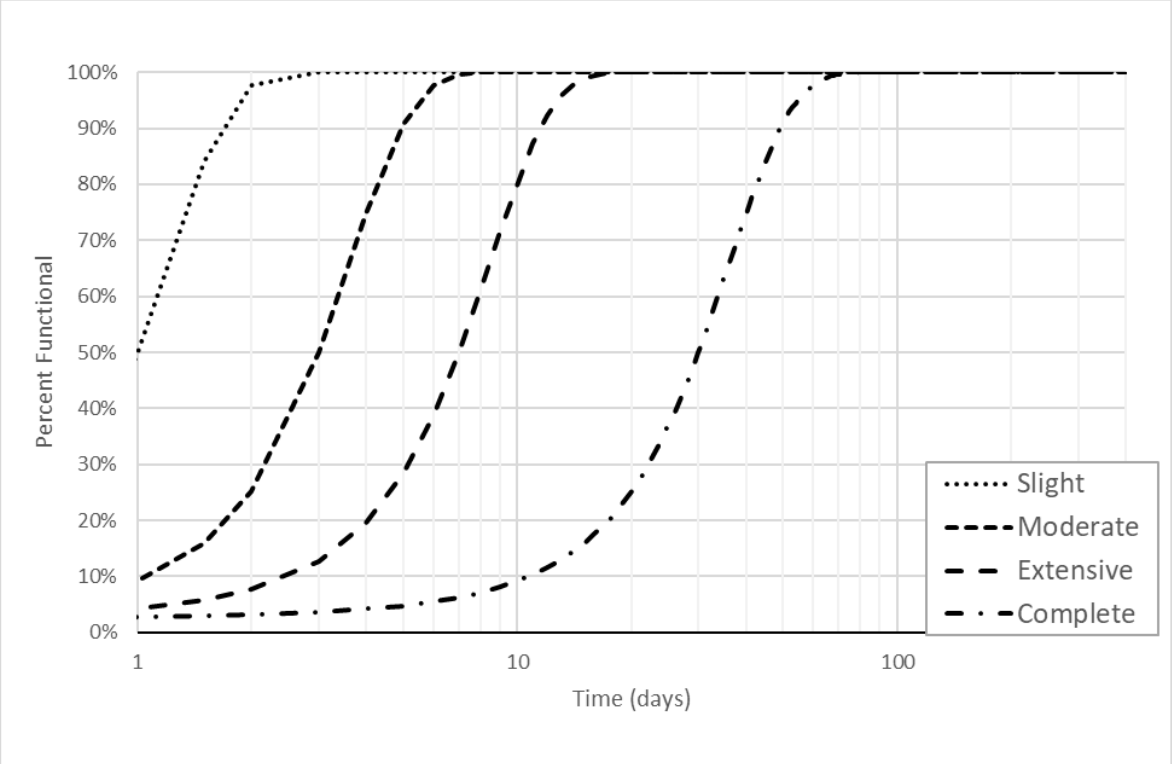


Figure 8-44 Restoration Curves for Electric Power Substations

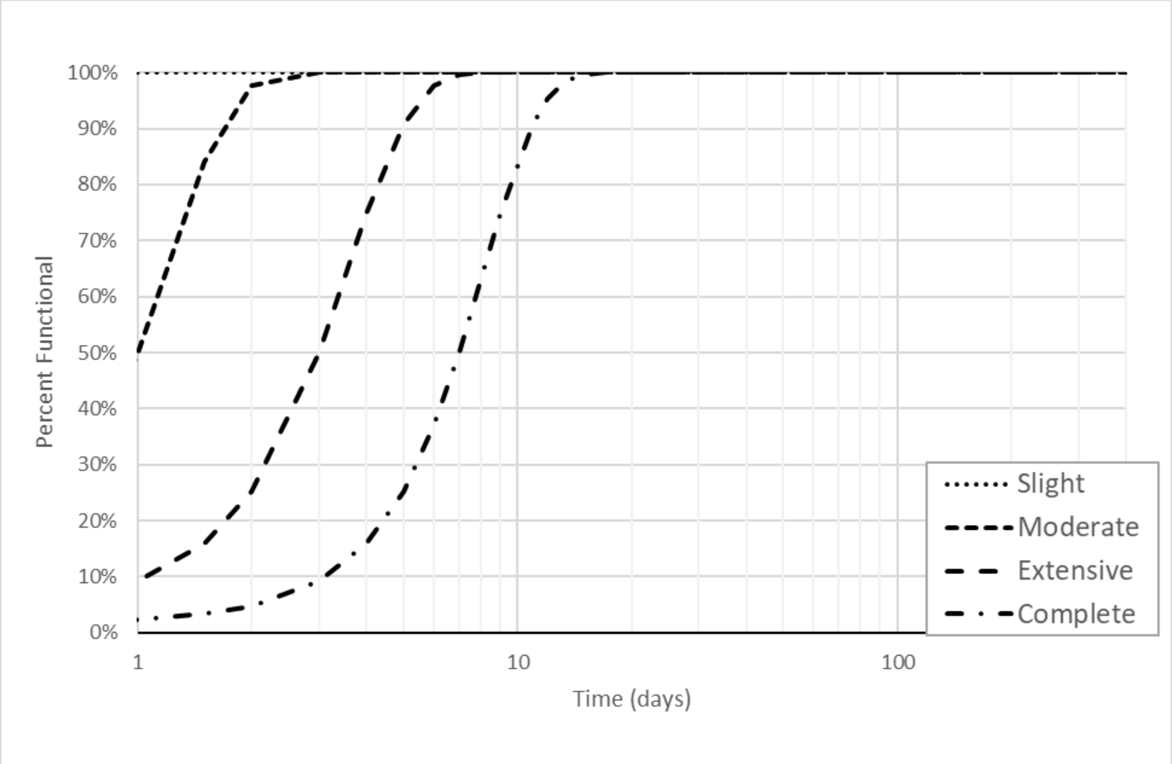


Figure 8-45 Restoration Curves for Distribution Circuits

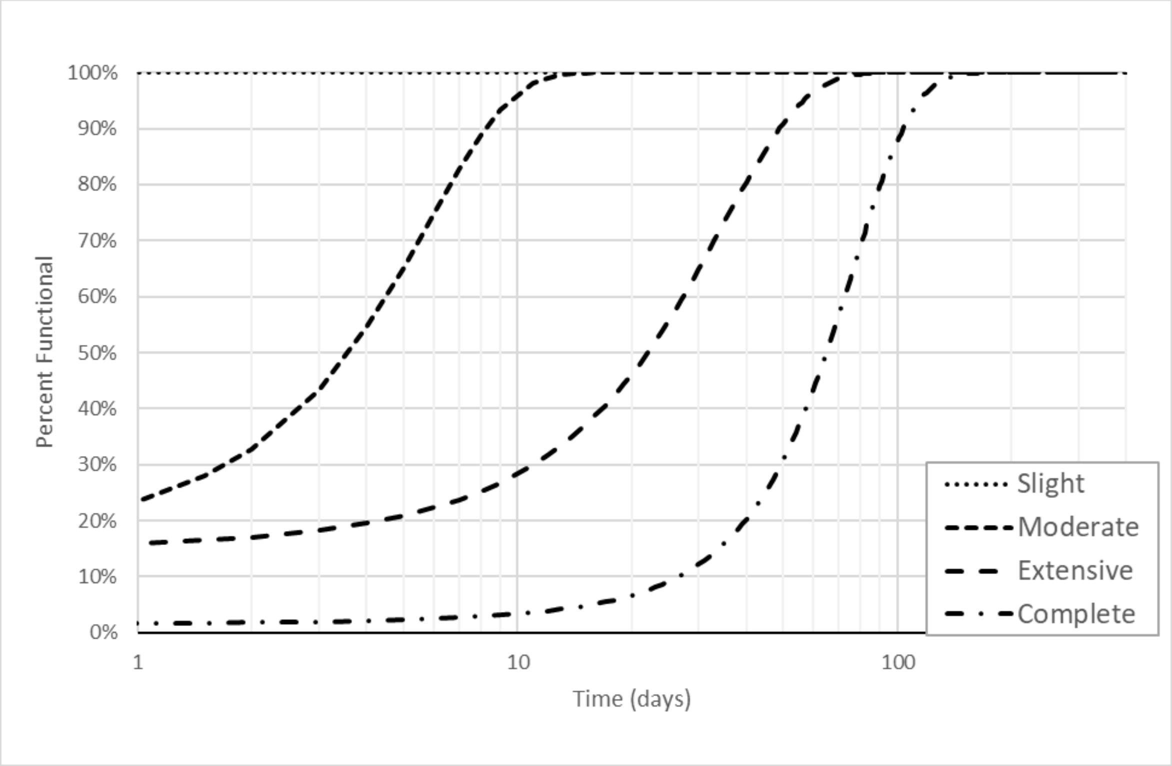


Figure 8-46 Restoration Curves for Generation Facilities

8.5.6 Development of Damage Functions

Fragility curves for electric power system components are defined with respect to classification and hazard 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, the failure of 40% of circuit breakers, 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 three “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. Further information on the electric power system facility subcomponent fragilities can be found in Appendix B.

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 8.1.6

8.5.6.1 Damage Functions for Electric Power Substations

PGA related damage functions for electric power substations are developed with respect to their classification. Medians and dispersions of these fragility functions are given in Table 8-29, and presented graphically in Figure 8-47 through Figure 8-52. Damage functions available within Hazus are the functions for facilities with unanchored components. User's wishing to analyze facilities with anchored components can revise the existing damage functions through the Hazus menus.

Table 8-29 Peak Ground Acceleration Fragility Functions for Substations

Classification	Damage State	Median (g)	β
Low voltage substations (ESSL) with anchored/seismic components (ESSL)	Slight	0.15	0.70
	Moderate	0.29	0.55
	Extensive	0.45	0.45
	Complete	0.90	0.45
Low voltage substations (ESSL) with unanchored/standard components	Slight	0.13	0.65
	Moderate	0.26	0.50
	Extensive	0.34	0.40
	Complete	0.74	0.40
Medium voltage substations (ESSM) with anchored/seismic components (ESSM)	Slight	0.15	0.60
	Moderate	0.25	0.50
	Extensive	0.35	0.40
	Complete	0.70	0.40
Medium voltage substations (ESSM) with unanchored/standard components	Slight	0.10	0.60
	Moderate	0.20	0.50
	Extensive	0.30	0.40
	Complete	0.50	0.40
High voltage substations (ESSH) with anchored/seismic components (ESSH)	Slight	0.11	0.50
	Moderate	0.15	0.45
	Extensive	0.20	0.35
	Complete	0.47	0.40
High voltage substations (ESSH) with unanchored/standard components (ESS6)	Slight	0.09	0.50
	Moderate	0.13	0.40
	Extensive	0.17	0.35
	Complete	0.38	0.35

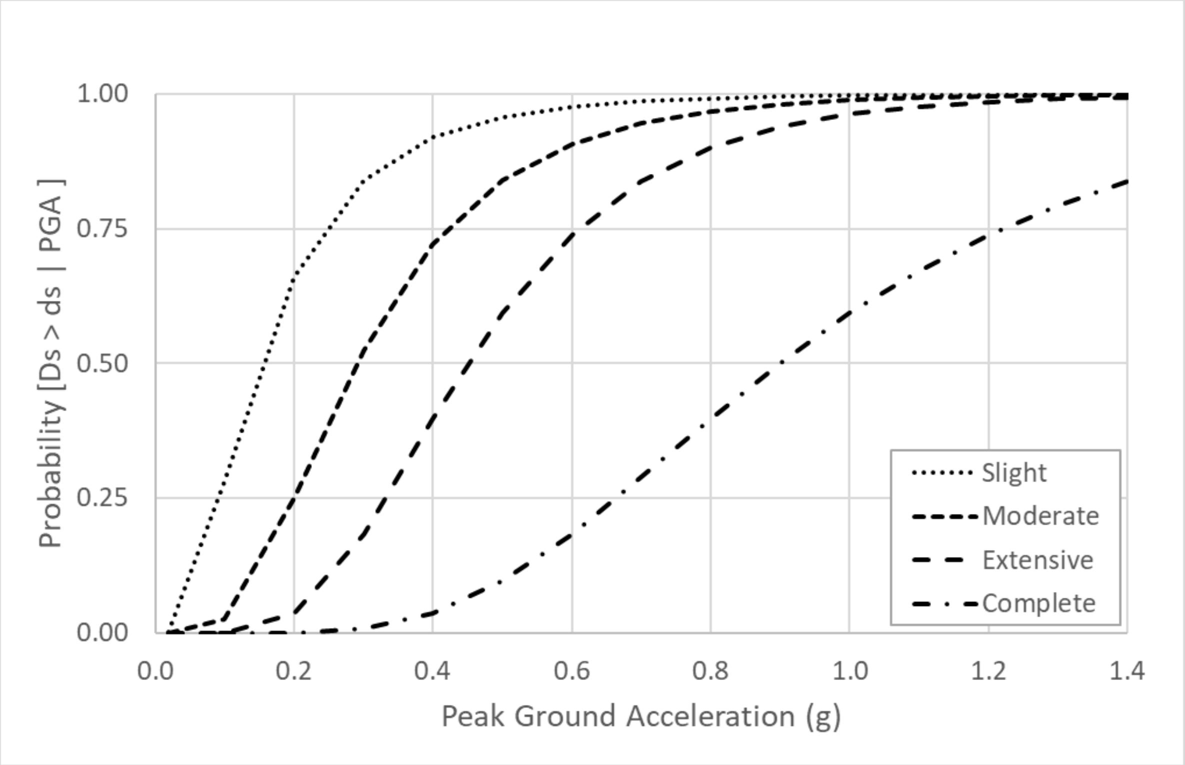


Figure 8-47 Fragility Curves for Low Voltage Substations with Anchored/Seismic Components

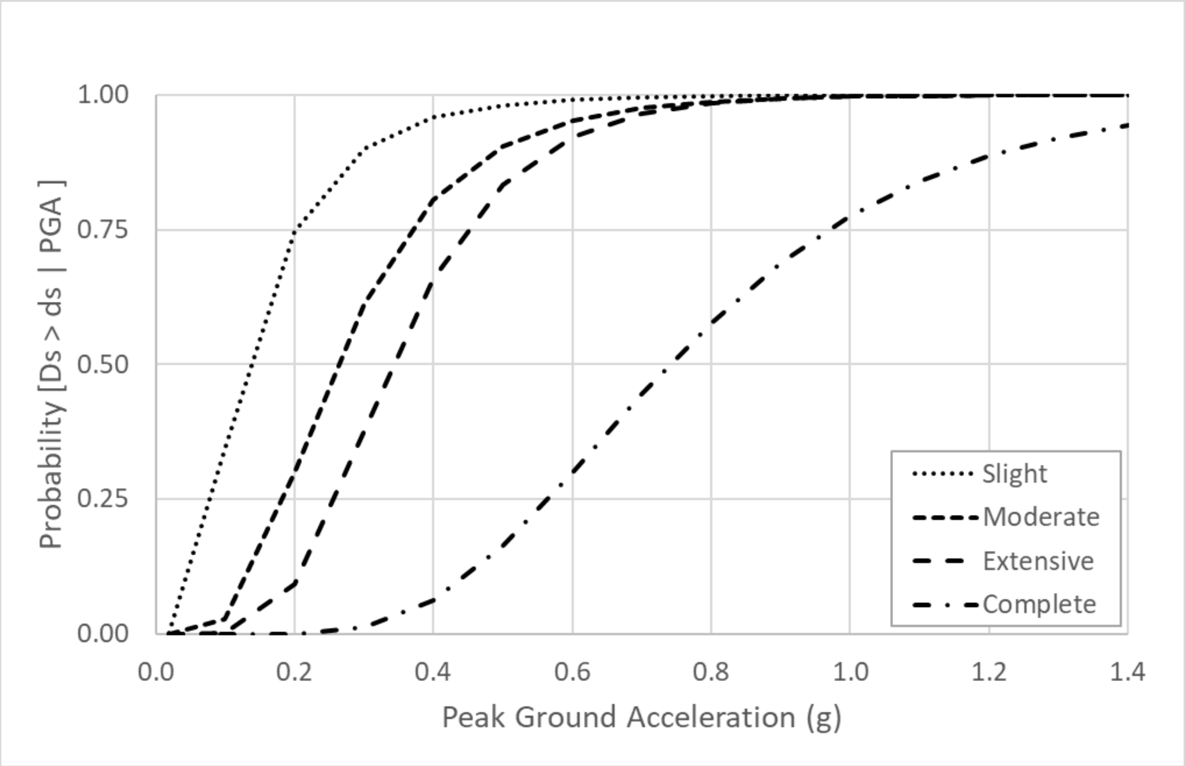


Figure 8-48 Fragility Curves for Low Voltage Substations with Unanchored/Standard Components

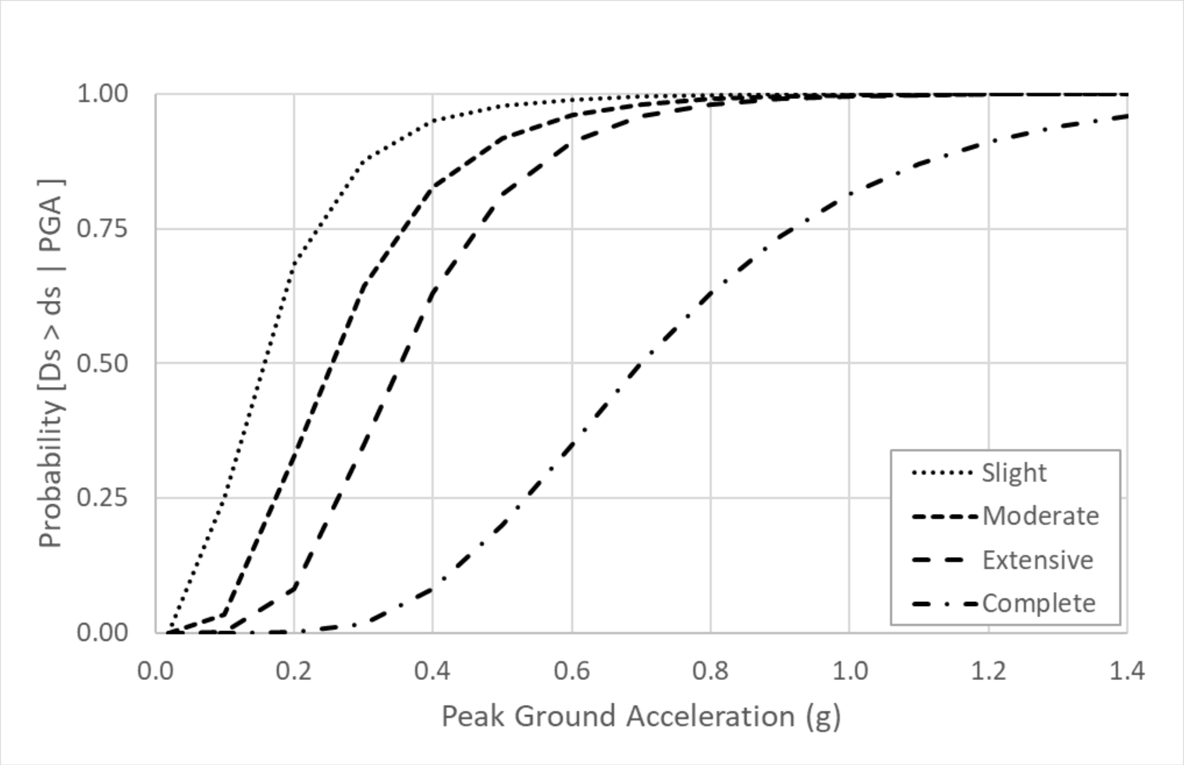


Figure 8-49 Fragility Curves for Medium Voltage Substations with Anchored/Seismic Components

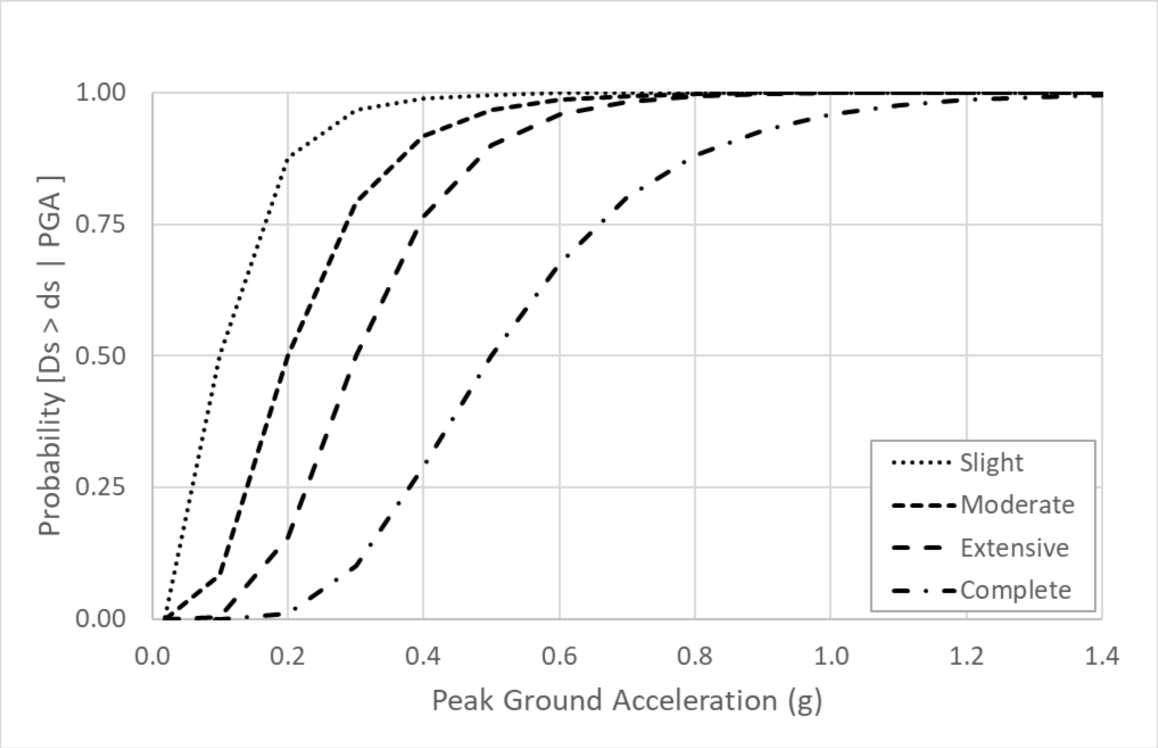


Figure 8-50 Fragility Curves for Medium Voltage Substations with Unanchored/Standard Components

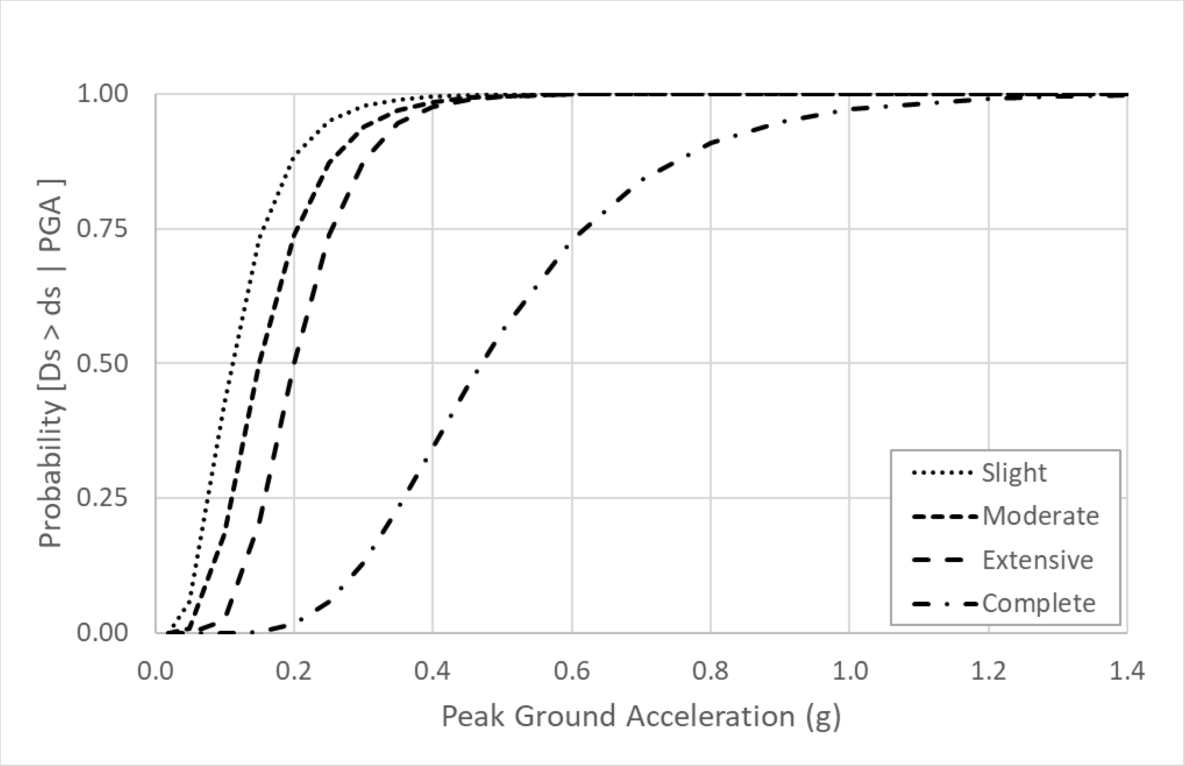


Figure 8-51 Fragility Curves for High Voltage Substations with Anchored/Seismic Components

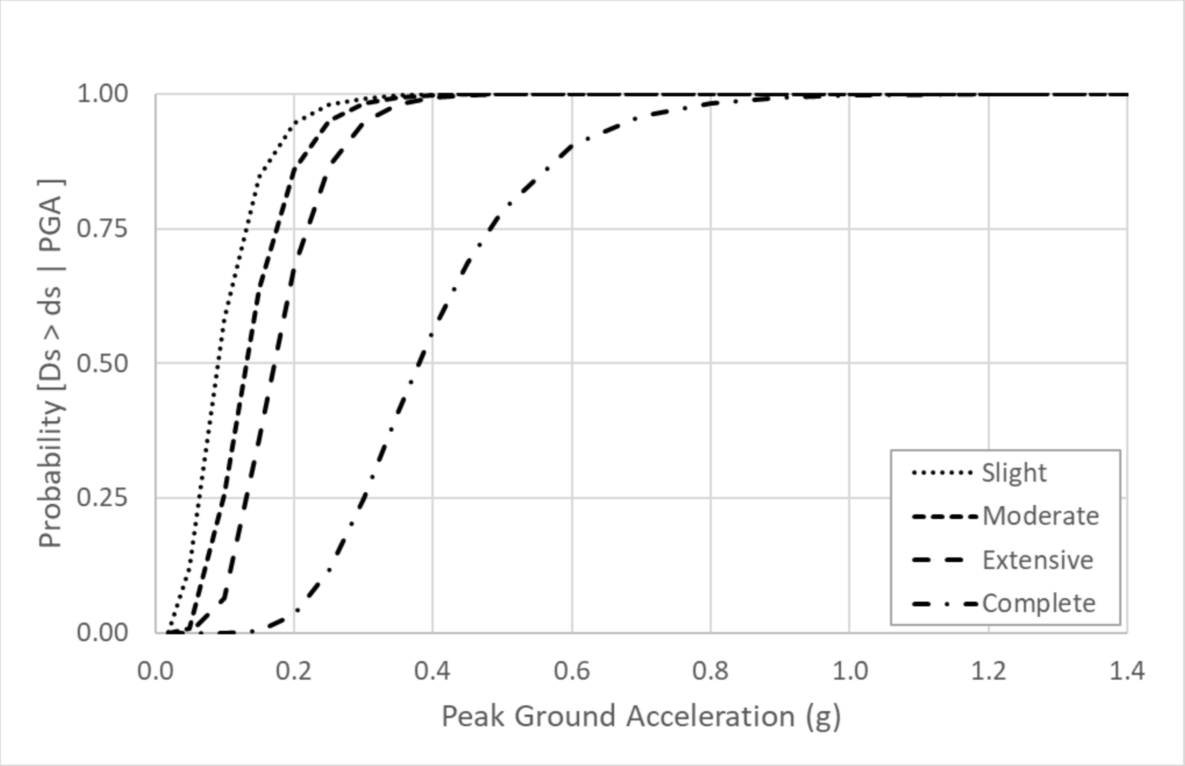


Figure 8-52 Fragility Curves for High Voltage Substations with Unanchored/Standard Components

8.5.6.2 Damage Functions for Distribution Circuits

PGA related damage functions for distribution circuits are developed with respect to their classification. Medians and dispersions of these damage functions are presented in Table 8-30 and are plotted in Figure 8-53 and Figure 8-54.

Table 8-30 Peak Ground Acceleration Fragility Functions for Distribution Circuits

Classification	Damage State	Median (g)	β
Anchored/Seismic Components (EDC)	Slight	0.28	0.30
	Moderate	0.40	0.20
	Extensive	0.72	0.15
	Complete	1.10	0.15
Unanchored/Standard Components (EDC)	Slight	0.24	0.25
	Moderate	0.33	0.20
	Extensive	0.58	0.15
	Complete	0.89	0.15

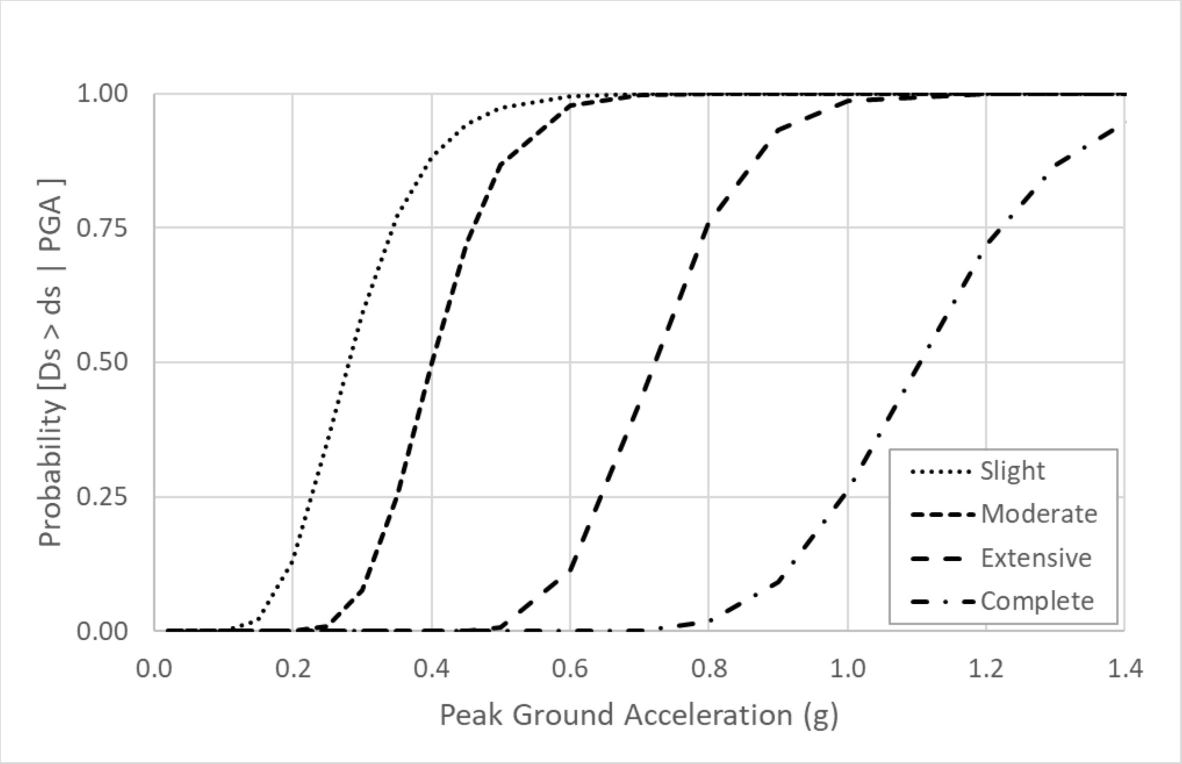


Figure 8-53 Fragility Curves for Anchored/Seismic Distribution Circuits

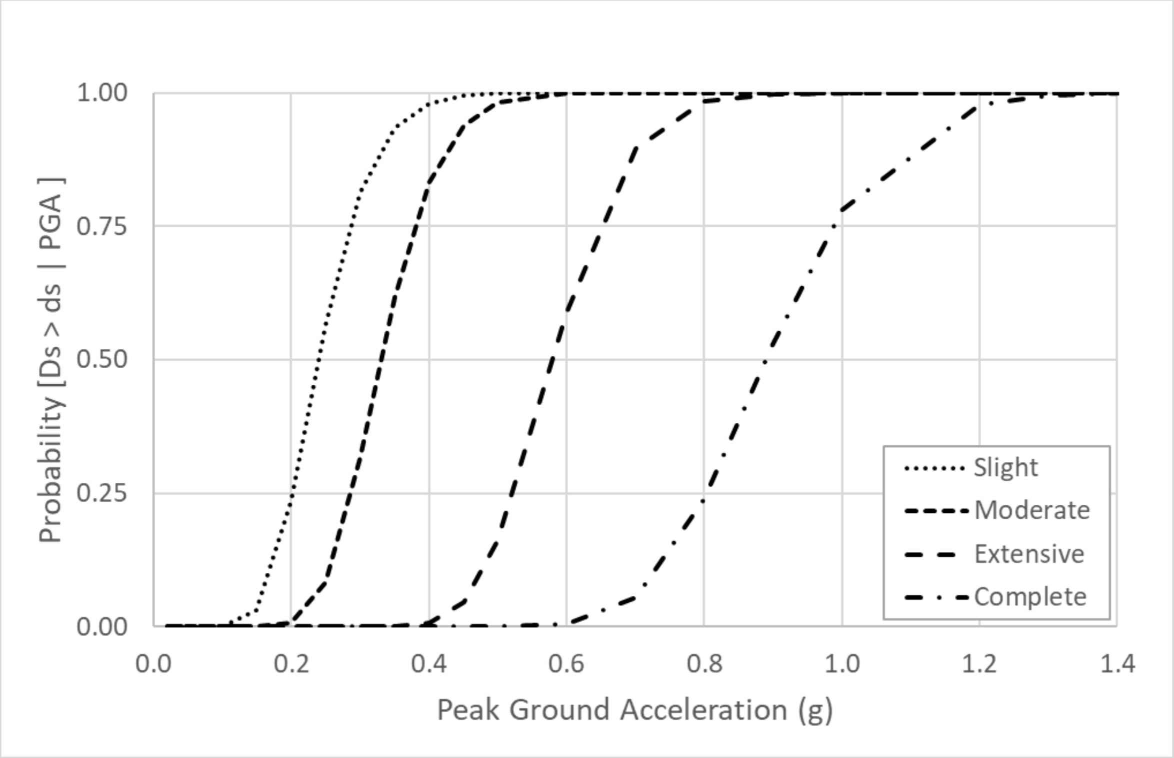


Figure 8-54 Fragility Curves for Unanchored/Standard Distribution Circuits

8.5.6.3 Damage Functions for Generation Plants

PGA related damage functions for power generation plants are developed with respect to their classification. Damage functions are provided for small generation plants (less than 100 MW) and medium/large plants (more than 100 MW). Medians and dispersions of these damage functions are given in Table 8-31 and Table 8-32. These fragility curves are shown in Figure 8-55 through Figure 8-58.

Table 8-31 Peak Ground Acceleration Fragility Functions for Small Generation Facilities

Classification	Damage State	Median (g)	β
Small Generation Facilities (EPPS) with Anchored Components	Slight	0.10	0.55
	Moderate	0.21	0.55
	Extensive	0.48	0.50
	Complete	0.78	0.50
Small Generation Facilities (EPPS) with Unanchored Components	Slight	0.10	0.50
	Moderate	0.17	0.50
	Extensive	0.42	0.50
	Complete	0.58	0.55

Table 8-32 Peak Ground Acceleration Fragility Functions for Medium/Large Generation Facilities

Classification	Damage State	Median (g)	β
Facility with Anchored Components (EPP3)	Slight	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	0.10	0.60
	Moderate	0.22	0.55
	Extensive	0.49	0.50
	Complete	0.79	0.50

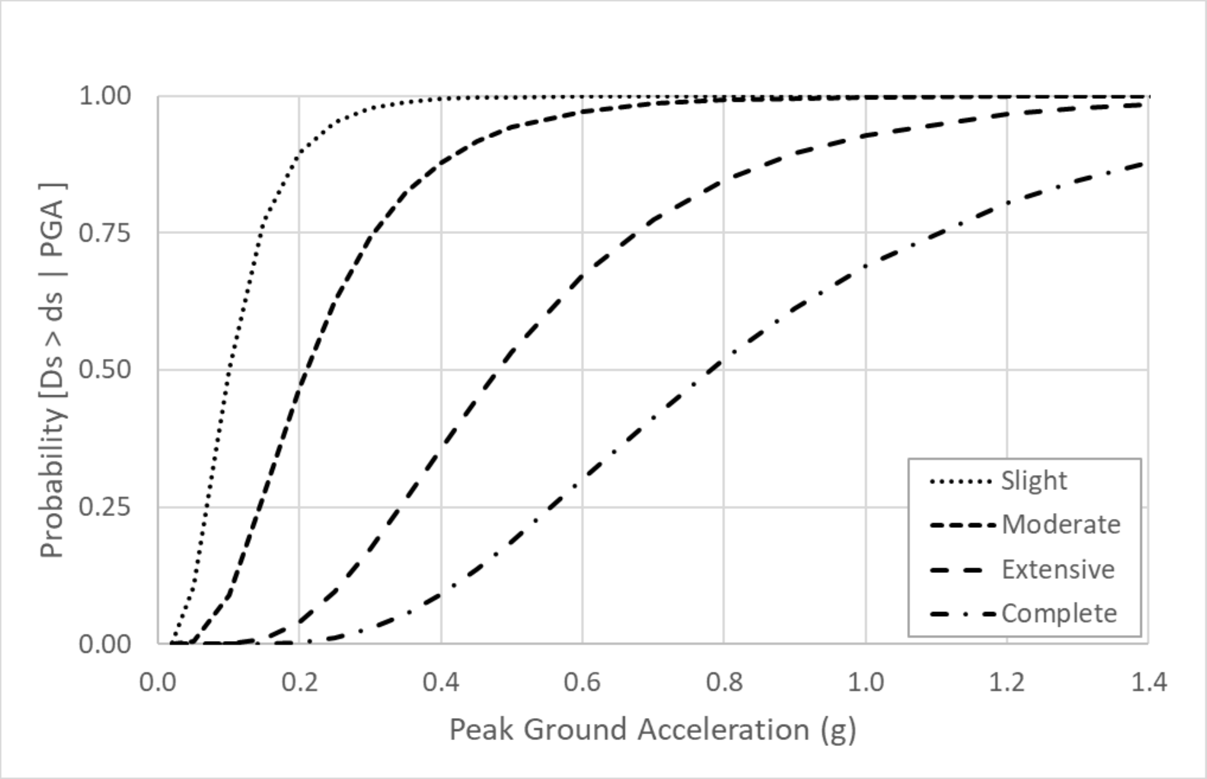


Figure 8-55 Fragility Curves for Small Generation Facilities with Anchored Components

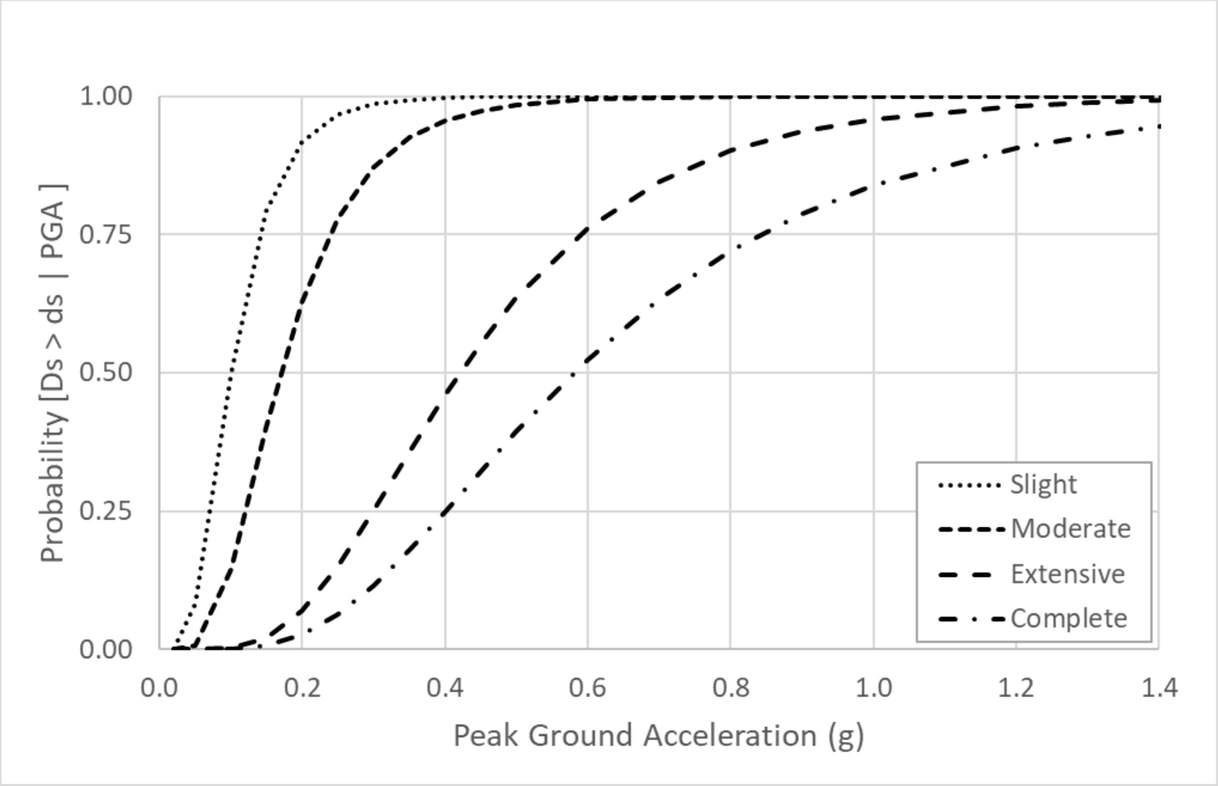


Figure 8-56 Fragility Curves for Small Generation Facilities with Unanchored Components

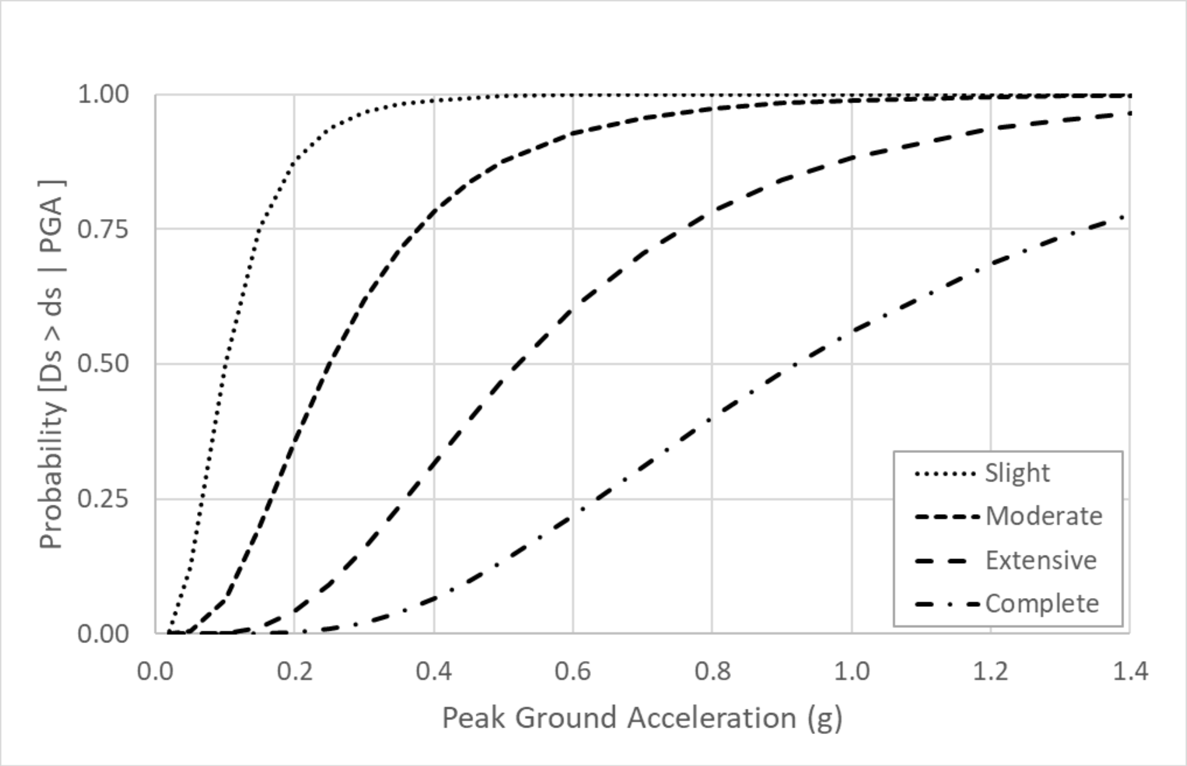


Figure 8-57 Fragility Curves for Medium/Large Generation Facilities with Anchored Components

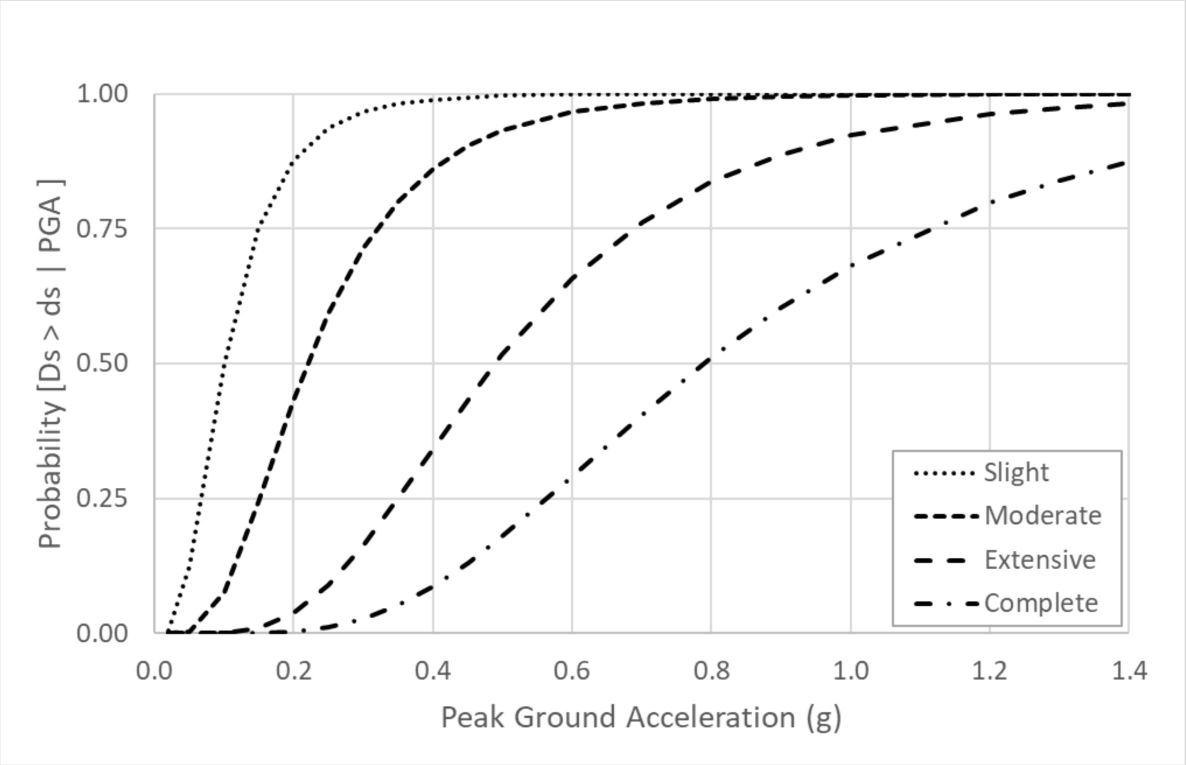


Figure 8-58 Fragility Curves for Medium/Large Generation Facilities with Unanchored Components

8.5.7 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. Substations are, in fact, among the more vulnerable electric power components in earthquakes, and damage to these facilities can affect wide areas.

Example

Assume that in a Study Region in the Western US, there are two medium voltage substations, both with anchored, seismically designed subcomponents. At one facility the PGA is 0.15g, while at the other facility the PGA is 0.3g. The electric power system performance is evaluated in this example. The fragility and restoration functions for medium voltage substations are reproduced in Table 8-33, Table 8-34, and Table 8-35.

Table 8-33 Example Fragility Function for Medium Voltage Substations with Seismic Components

Damage State	Median (g)	β
Slight	0.15	0.6
Moderate	0.25	0.5
Extensive	0.35	0.4
Complete	0.7	0.4

Table 8-34 Example Restoration Functions (All Normal Distributions)

Damage State	Mean (days)	(days)
Slight	1.0	0.5
Moderate	3.0	1.5
Extensive	7.0	3.5
Complete	30.0	15.0

Table 8-35 Example Discretized Restoration Functions

Damage State	3 days	7 days	30 days	90 days
Slight	100	100	100	100
Moderate	50	100	100	100
Extensive	13	50	100	100
Complete	4	7	50	100

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

At Substation 1,

$$\mathrm{P}[\mathrm{D_S} = \mathrm{None}|\mathrm{PGA} = 0.15\mathrm{g}] = 0.50$$

$$\mathrm{P}\ [\mathrm{D_S} = \mathrm{Slight}\ |\ \mathrm{PGA} = 0.15\mathrm{g}] = 0.35$$

$$\mathrm{P}\ [\mathrm{D_S} = \mathrm{Moderate}\ |\ \mathrm{PGA} = 0.15\mathrm{g}] = 0.13$$

$$\mathrm{P}\ [\mathrm{D_S} = \mathrm{Extensive}\ |\ \mathrm{PGA} = 0.15\mathrm{g}] = 0.02$$

$$\mathrm{P}\ [\mathrm{D_S} = \mathrm{Complete}|\ \mathrm{PGA} = 0.15\mathrm{g}] = 0.00$$

At Substation 2,

$$\mathrm{P}\ [\mathrm{D_S} = \mathrm{None}\ |\ \mathrm{PGA} = 0.3\mathrm{g}] = 0.12$$

$$\mathrm{P}\ [\mathrm{D_S} = \mathrm{Slight}\ |\ \mathrm{PGA} = 0.3\mathrm{g}] = 0.24$$

$$\mathrm{P}\ [\mathrm{D_S} = \mathrm{Moderate}\ |\ \mathrm{PGA} = 0.3\mathrm{g}] = 0.29$$

$$\mathrm{P}\ [\mathrm{D_S} = \mathrm{Extensive}\ |\ \mathrm{PGA} = 0.3\mathrm{g}] = 0.33$$

$$\mathrm{P}\ [\mathrm{D_S} = \mathrm{Complete}\ |\ \mathrm{PGA} = 0.3\mathrm{g}] = 0.02$$

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

Equation 8-3

$$\mathrm{FP_C} = \sum_{\mathrm{i=1}}^{\mathrm{i=5}} \mathrm{FR_i} * \mathrm{P}[\mathrm{ds_i}]$$

Where:

FPc is the combined facility functionality

FRi	is the facility restoration percent for damage state i,
P[dsi]	is the occurrence probability of damage state i.

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

At substation # 1,

$$\mathrm{FP_C}\,[3\text{ days}] = (0.5 * 100\%) + (0.35 * 100\%) + (0.13 * 50\%) + (0.02 * 13\%) + (0.0 * 4\%) = 91.8\%$$

At substation # 2,

$$\mathrm{FP_c}[3\text{ days}] = (0.12 * 100\%) + (0.24 * 100\%) + (0.29 * 50\%) + (0.33 * 13\%) + (0.02 * 4\%) = 54.9\%$$

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 on average, 27% 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 by the number of households (housing units) in each Census tract and reported as a total for each county.

Finally, it should be mentioned that the interaction between electric power and other utility systems was considered marginally through a fault tree analysis. Loss of electric power is assumed to affect only the Slight and Moderate damage states of other utility 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 utility system components it interacts with will be subject to a comparable level of ground motion.

8.6 Communication Systems

This section presents the earthquake loss estimation methodology for communication systems. 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 transmission lines, usually have enough slack to accommodate ground shaking and even moderate amounts of permanent ground deformations.

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., anchored or unanchored equipment), and the hazards (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., None, Slight, Moderate, Extensive, or Complete). Fragility curves are developed for each classification of communication facility. 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, the functionality of each facility can be assessed.

8.6.1 Input Requirements and Output Information

Required input to estimate damage to central offices and broadcasting stations in a communication system includes the following items:

- Classification (i.e., with anchored or unanchored components)
- Geographical location of the communication facility (longitude and latitude)
- PGA and PGD

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

8.6.2 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 or ground failure and an associated dispersion factor (lognormal standard deviation). Definitions of various damage states and the methodology used in deriving these fragility curves are presented in the following section.

8.6.3 Description of Communication System Components

As mentioned previously, only central office and broadcasting station facilities are considered. A communication facility consists of a building (a 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 facility in case of loss of off-site power.

8.6.4 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, Slight, Moderate, Extensive, and Complete.

Slight Damage

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

Moderate Damage

- Moderate damage is defined by Moderate damage to the communication facility building, a 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

- Extensive damage 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

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

8.6.5 Component Restoration Curves

Restoration functions are shown in Figure 8-59. The restoration functions given in Figure 8-59 are based on ATC-13 (ATC, 1985) 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 utility systems. The parameters of these restoration curves are given in Table 8-36 (continuous) and Table 8-37 (discretized). Although not directly used in Hazus, the discretized restoration functions are presented here as guidance.

Table 8-36 Continuous Restoration Functions for Communication Facilities (All Normal Distributions)

Classification	Damage State	Mean (Days)	σ (Days)
Communication facility	Slight	0.5	0.2
	Moderate	1	1
	Extensive	7	7
	Complete	40	40

Table 8-37 Discretized Restoration Functions for Communication Facilities

Classification	Damage State	Functional Percentage				
		1 day	3 days	7 days	30 days	90 days
Communication facility	Slight	99	100	100	100	100
	Moderate	50	98	100	100	100
	Extensive	20	28	50	100	100
	Complete	16	18	20	40	89

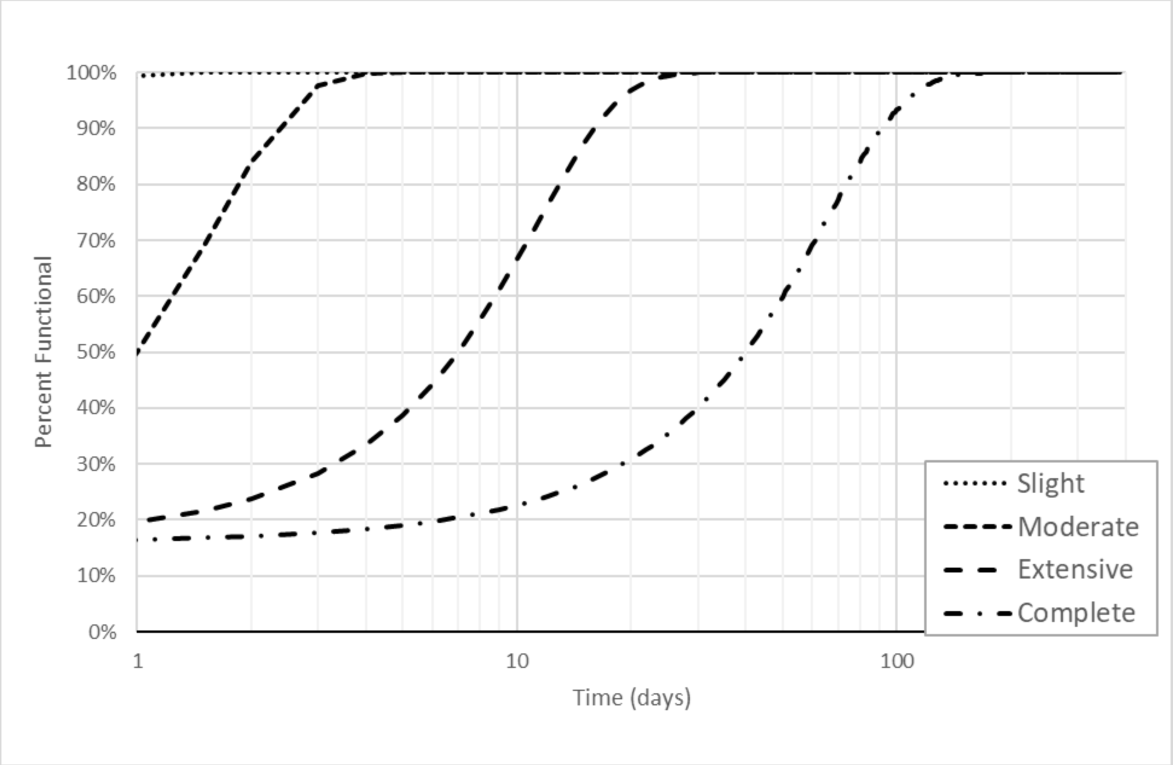


Figure 8-59 Restoration Curves for Central Offices

8.6.6 Development of Damage Functions

In this subsection, damage functions for the communication facilities (central offices and broadcasting stations) 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. Further information on the communication system facility subcomponent fragilities can be found in Appendix B: Subcomponent Damage Functions for Utility Systems. Note also that damage functions due to ground failure (i.e., PGD) for these facilities are assumed to be similar to those described for potable water system facilities in Section 8.1.6.

PGA related fragility functions are given in terms of median values and dispersions for each damage state in Table 8-38. These are plotted in Figure 8-60 and Figure 8-61. Damage functions available within Hazus are the functions for facilities with unanchored components. User's wishing to analyze facilities with anchored components can revise the existing damage functions through the Hazus menus.

Table 8-38 Peak Ground Acceleration Fragility Functions for Communication Facilities

Classification	Damage State	Median (g)	β
Facilities with anchored components	Slight	0.15	0.75
	Moderate	0.32	0.60
	Extensive	0.60	0.62
	Complete	1.25	0.65
Facilities with unanchored components	Slight	0.13	0.55
	Moderate	0.26	0.50
	Extensive	0.46	0.62
	Complete	1.03	0.62

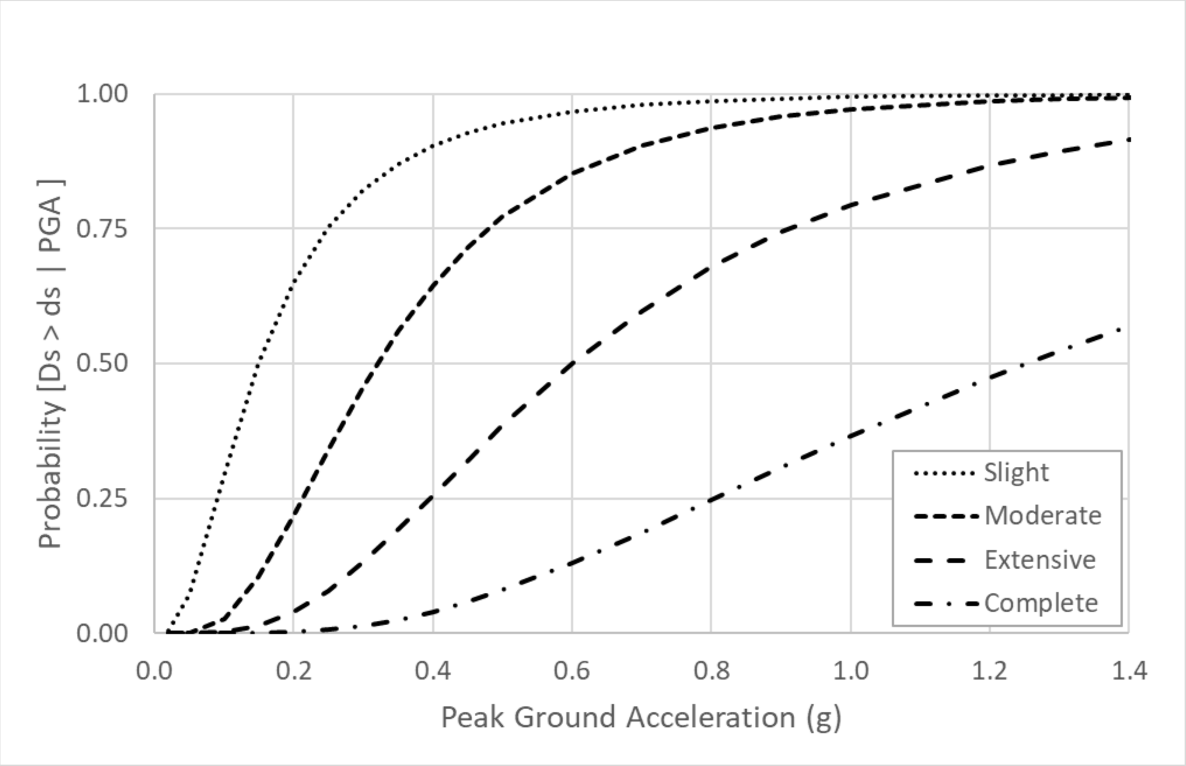


Figure 8-60 Fragility Curves for Communication Systems with Anchored Components

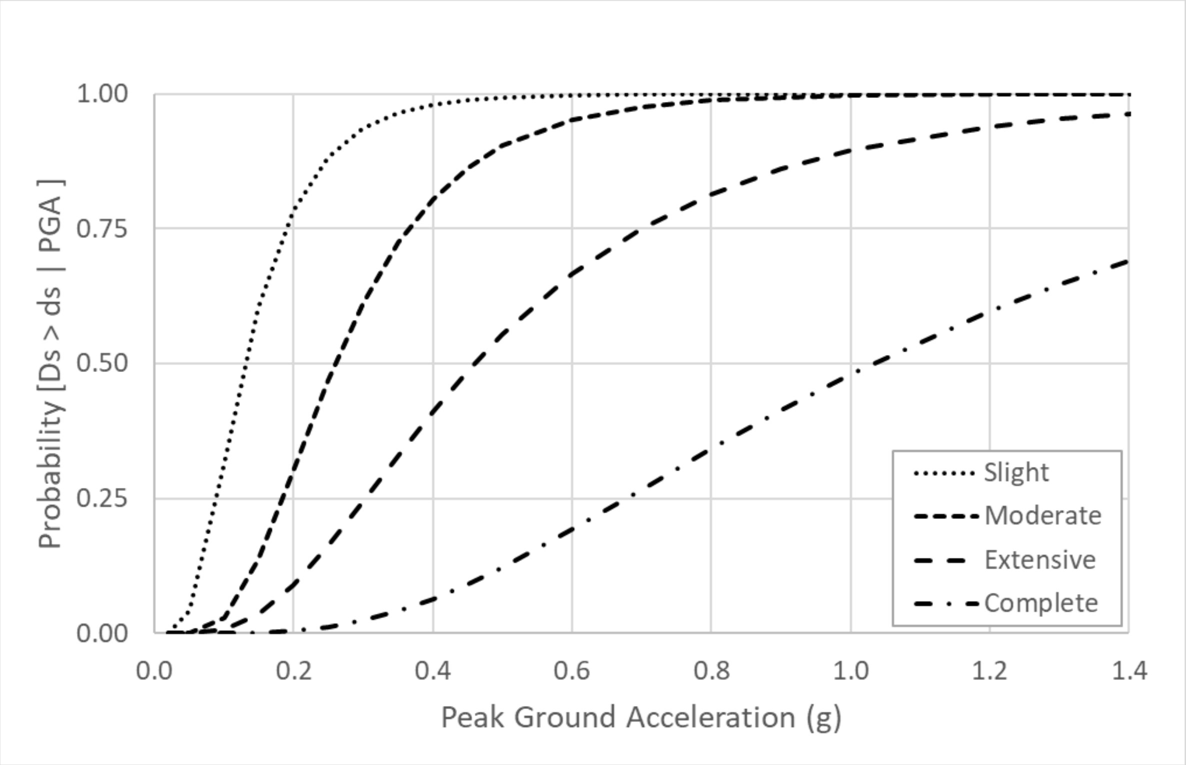


Figure 8-61 Fragility Curves for Communication Systems with Unanchored Components

Section 9. Induced Damage Modules – Fire Following Earthquake

Fires following earthquakes can cause severe losses. These losses can sometimes be greater than direct damage caused by the earthquake, such as the collapse of buildings and disruption of transportation and utility systems. The severity of fires following an earthquake can be affected by ignition sources, types and density of fuels, weather conditions, functionality of water systems, and the ability of firefighters to suppress the fires.

A complete fire following earthquake module requires extensive input with respect to the level of readiness of local fire departments and the types and availability (functionality) of water systems. The Hazus fire following earthquake module is simplified to reduce the input requirements and to account for simplifications in the utility and transportation systems modules. Additionally, the module should be considered a technology still in the maturing process, as it builds upon past efforts. There will undoubtedly be room for improvement in forecasting capabilities with better understanding of fires that will be garnered after future earthquakes.

9.1 Scope

A complete fire following earthquake (FFE) module encompasses the three phases of a fire:

- Ignition
- Spread
- Suppression

This methodology provides the user with the following estimates:

- Number of ignitions
- Total burned area
- Population exposed to the fires
- Building value consumed by the fire

Using Baseline and User-Supplied Data will provide an estimate of the magnitude of the FFE problem, that could be used to plan for and estimate demands on local firefighting resources.

9.1.1 Form of Damage Estimates

The FFE methodology provides the following:

- An estimate of the number of serious fire ignitions that will require fire department response after an earthquake
- An estimate of the total burned area
- An estimate of the population and building exposure affected by the fire

By applying the FFE module for several scenario earthquakes, representing different potential earthquakes for the study area with different recurrence intervals, the user can examine the efficacy of certain pre-earthquake actions used to mitigate the potential losses from fires in future earthquakes. For example, the user could study the effect of building more fire stations, adding more fire apparatuses, improving immediate post-earthquake response to detect fires and suppress fires before they spread, or seismically upgrading the water system. Since all these activities cost money, the user could do a benefit cost analysis to study which combination of activities is most beneficial to their communities.

9.1.2 Input Requirements

This section describes the inputs required and output provided by the FFE module.

Input for Analysis

Provided as part of the general building stock baseline inventory data:

- Square footage of residential single-family dwellings (SFD)
- Square footage of residential non-SFD
- Square footage of commercial buildings
- Square footage of industrial buildings

Provided as part of the essential facility baseline inventory data:

- Number of fire stations
- Geographical location of each station
- Number of engines at each fire station (note: this is user-supplied data)

Provided by the PEH module:

- PGA

Analysis options input by the user:

- Wind speed
- Wind direction
- Speed of the fire engine truck(s) (after the earthquake)
- Number of simulations
- Maximum simulation time
- Simulation time increment

The module produces multiple estimates of fire impacts for the same earthquake scenario, which are calculated by simulating the fire following earthquake scenarios several times. Therefore, the user needs to provide the number of simulations that should be performed to produce the average estimates from independent simulations. It is suggested that the user select a value between 6 and 10 simulations. The baseline value is 10 simulations. The user will assign the maximum time after the earthquake the simulation should be performed, and the time increment for each simulation. For example, a reasonable maximum time could be 10,000 minutes (approximately one week) when all the fires could possibly be suppressed. The baseline value is 1440 minutes (one day). It is suggested that time increments between 1 to 15 minutes (baseline value is 5 minutes) be selected for more accurate simulations.

9.2 Description of Methodology

9.2.1 Ignition

When evaluating the potential losses due to fires following earthquake, the first step is to estimate the number of fires that actually occur after the earthquake. The ignition model is based on the number of serious FFEs that have occurred after previous earthquakes in the United States.

The term "ignition" refers to each individual fire that starts (ignites) after an earthquake that requires fire department response to suppress. Thus, a fire that starts after an earthquake but is put out by the occupants of the building without a response from the fire department is not considered an ignition for the purpose of this model. Fires that are put out by building occupants are usually discovered very early and put out before they can cause substantial damage. These ignitions do not lead to significant losses.

Ignitions are calculated on the basis of an “ignition rate”, which is the frequency of ignitions normalized by a measure of the potential source of ignitions. For Hazus, the ignition rate is the frequency of ignitions per million square feet of total building floor area per district considered.

Ignition rates for use in Hazus were determined according to an empirical statistical analysis (SPA Risk, 2009), described in the following sections.

9.2.1.1 Ignition Data Sources

Initially, all 20th century earthquakes, in the U.S. as well as in other countries, were considered as potential data sources for post-earthquake ignitions. Several criteria were used to focus on selected events for analysis:

- Only events that had ignitions (defined as an individual fire that starts/ignites after an earthquake that ultimately requires fire department response to suppress) were considered.
- Ultimately, only U.S. data were used. Use of non-U.S. data was considered early in the development of the ignition model, but the idea was rejected because most non-U.S. data are derived from Japan, which was problematic due to homogeneity issues. While Japan is an advanced technological society like the U.S., with comparable safety and other standards, the residential building construction in Japan differs significantly from that in the U.S. A simple example suffices: the 1994 Mw 6.7 Northridge earthquake in southern California affected a population of perhaps 3 million people within the MMI VI isoseismal, had relatively few collapsed buildings, approximately 110 ignitions and 67 people killed. The 1995 Mw 6.9 Hanshin Awaji (Kobe) earthquake in Japan comparably affected perhaps 1.5 million people, had thousands of collapsed buildings (majority residential), approximately 110 ignitions and 6,000 people killed (Scawthorn 1996).
- Post-1970 data were employed. Use of earlier events was considered as previous analyses, including that for Hazus, have used data as far back as 1906, and there are some arguments for still doing this. However, the changes in building, household appliance, and industrial safety standards, and the nature of the urban region (post-industrial), support the argument to only use more recent data. Because the 1971 San Fernando event was considered still relevant, 1970 was selected as the cut-off date.

Using these criteria, seven earthquake events were identified with significant data and adequate documentation:

- 1971 San Fernando
- 1983 Coalinga
- 1984 Morgan Hill
- 1986 N. Palm Springs
- 1987 Whittier Narrows
- 1989 Loma Prieta
- 1994 Northridge

The data identified a total of 238 ignitions, which are summarized in Table 9-1, and the distribution of ignitions relative to ground shaking are shown in Figure 9-1.

Table 9-1 Summary of Ignition Data Used to Develop the Hazus FFE Ignition Equation

Earthquake	# Ignitions in Data Set	Source of Data
1971 San Fernando	91	Unpublished data
1983 Coalinga	3	(Scawthorn 1984)
1984 Morgan Hill	6	(Scawthorn 1985)
1986 N. Palm Springs	1	(EERI 1986)
1987 Whittier Narrows	20	(Wiggins 1988)
1989 Loma Prieta	36	(Mohammadi et al. 1992; Scawthorn 1991)
1994 Northridge	81	(Scawthorn et al. 1997)
Total # of Ignitions	**238**	

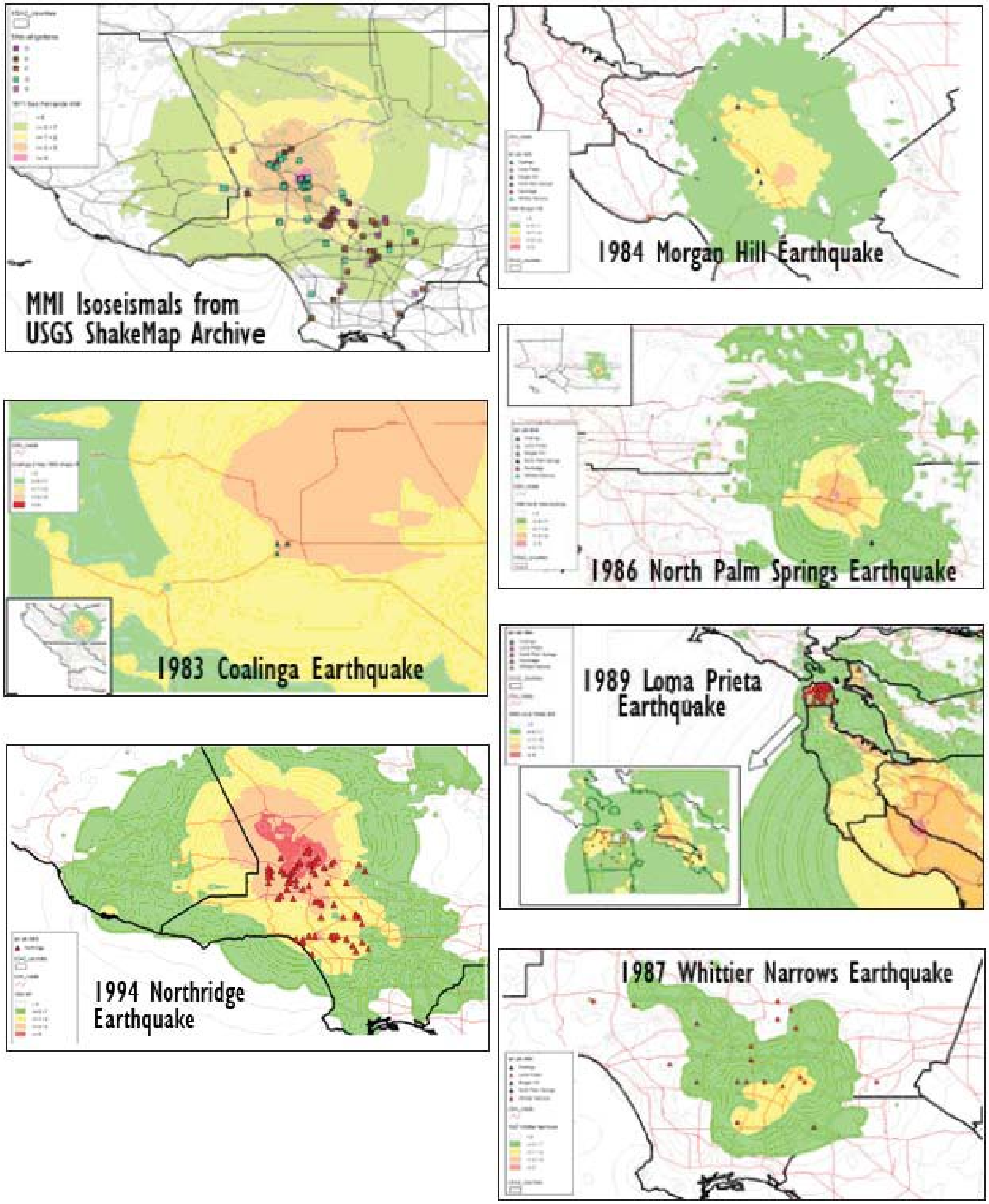


Figure 9-1 Distribution of Ignitions vs. MMI in Seven Selected Earthquakes

9.2.1.2 Ground Motions

For correlating ignition data with ground motions, the USGS ShakeMap archive provided consistent high-quality data sets for these seven events, in terms of Modified Mercalli Intensity (MMI), Peak Ground Acceleration (PGA), Peak Ground Velocity (PGV), and Spectral Acceleration (for 0.3 sec, SA0.3). Note that the ShakeMaps include local soil conditions and site effects, within the limitations of the relevant databases.

9.2.1.3 Development of the Ignition Equation

The specific approach employed for determining the post-earthquake ignition rate was to overlay the ignition data discussed above on a relatively detailed mesh of the areas affected in each event, in order to determine ignition rates normalized by some measure of the earthquake intensity and exposure of potential ignition sources. Where previous studies had used 'city' sized data points, meshes considered here were regular grids (e.g., 1 km square), Census tracts, fire battalion districts, and postal codes. After some preliminary analysis, Census tracts (from the 2000 Census) were chosen as the level of granularity for the analysis. To produce a fine mesh, only a few tracts had more than one ignition. For the seven event data sets, use of Census tracts resulted in a large number of tracts. To identify a more meaningful subset of tracts, the model utilized two criteria:

- *Intensity*: only Census tracts experiencing peak ground acceleration of 0.13g (MMI VI) or greater were employed in the analysis to develop the ignition equation. Previous analyses have shown that at MMI VI or less, ignition rates are negligible. The inclusion of tracts with less than MMI VI shaking would result in a weak 'signal-noise' ratio for the analysis. Culling tracts with MMI VI or less resulted in loss of a few ignition points. The Hazus software currently uses a lower threshold ground shaking value (0.051g) in applying the ignition equation.
- *Population Density*: only Census tracts with population density of 3,000 persons per square kilometer or greater were employed in the analysis to develop the ignition equation, and are utilized in Hazus in estimating ignitions. Tracts with lower population densities have a weak 'signal-noise' ratio and, more importantly, the fire following earthquake problem is relatively negligible in sparsely populated tracts, as fire spread in these areas is typically insignificant. Additionally, only moderately or greater populated areas contain sufficient concentrations of housing and infrastructure that would result in significant ignition rate. For reference:
    - Los Angeles - the average population density of the entire City of Los Angeles is 3,168 per sq. km. (total 2006 population 3,849,378 and total area 1,290.6 sq. km.), with some Census tracts having densities as high as 18,000 people per sq. km.
    - Berkeley (Alameda County) has a population density of 3,792
    - The City of San Francisco has a population density of 6,607 people per sq. km, with some tracts over 20,000 people per sq. km.

Effectively, these two criteria (PGA ≥ 0.13g, population density ≥ 3,000 per sq. km.) restricted the ignition rate development analysis to urban settings where fire following earthquake is a significant concern. Using these two criteria reduced the number of Census tracts for the seven events to 1,435. The frequency distribution of PGA for this group of Census tracts is shown in Figure 9-2. Note that virtually 100% of the data set experienced ground motions greater than 0.2g. Since some of the Census tracts had experienced more than one ignition in an earthquake, the resulting number of Census tracts with ignition data is 155, or about 10.8% of the data set. That is, 1,380 tracts (89.2%) are "zero-ignition" points.

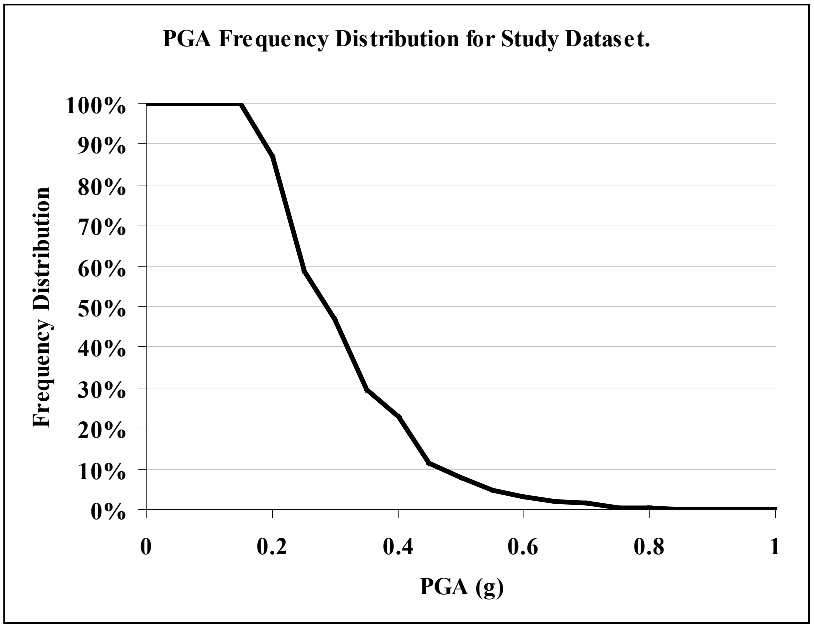


Figure 9-2 PGA Frequency Distribution for the Study Data Set (n=1,435)

For each Census tract in the resulting data set, the analysis normalized the number of ignitions by several measures, including (a) building total floor area for all buildings, and for various combinations of specific building types (e.g., total floor area for only wood framed buildings, total floor area for wood framed and unreinforced masonry buildings, etc); (b) weighted averages of various combinations of total floor area of damaged buildings; and (c) other socio-economic measures, such as population and “built-upness” (total floor area density). Each of these measures were regressed against the several measures of ground motion (MMI, PGA, PGV, SA0.3), for several functional forms – linear, polynomial, semi-log, and power law. The criterion for best fit was correlation coefficient. While a number of combinations of covariates were examined, the best result was a polynomial equation (Equation 9-1) relating ignitions per million sq. ft. of total floor area, with PGA. The correlation coefficient for this formulation was R2 = 0.084.

Equation 9-1

$$\frac{\mathrm{Ign}}{\mathrm{TFA}} = 0.581895(\mathrm{PGA})^2 - 0.029444(\mathrm{PGA})$$

Where:

$\frac{\mathrm{Ign}}{\mathrm{TFA}}$ is the mean number of ignitions per million sq. ft. of building total floor area in the area of interest (e.g., Census tract, although the equation is applicable to any area).

Equation 9-1 and the analysis data are plotted versus PGA in Figure 9-3. Analysis shows the distribution of the logarithm of the data-regression residuals may be approximated as a normal distribution with mean of zero and standard deviation of 0.12.

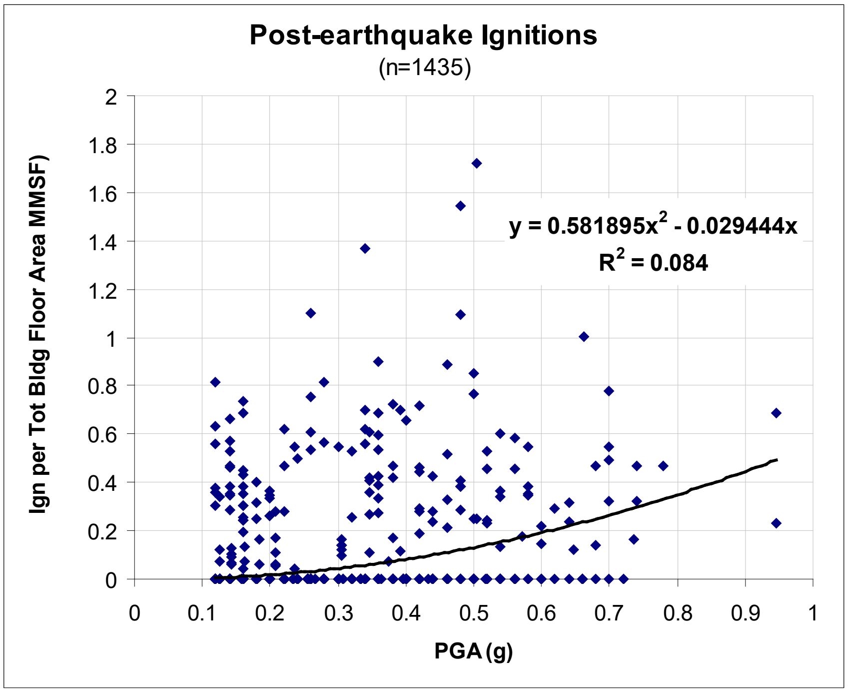


Figure 9-3 Ignition Rate Data and Regression as Function of PGA (n=1,435)

9.2.1.4 Temporal distribution of Ignitions

The equation for ignition rates is empirical and includes fires, both those starting immediately after the earthquake, and starting some time after the earthquake. Empirical analysis indicates that about 20% of the ignitions will have occurred within the first hour, about half will have occurred within 6 hours, and almost all will have occurred by the end of the first day. Note that while fire departments typically have response goals of only several minutes, the time on-scene for a structural fire is typically several hours, so departments will be occupied with the first wave of fires as others are continuing to ignite (see SPA Risk, 2009 for further details).

9.2.2 Spread

The second step in performing the FFE analysis is to estimate the spread of the initial fire ignition. The following description of fire spread in urban areas is based on a model developed by Hamada (1975), for fire spreading for urban Japan. The Hamada model is described as follows:

Equation 9-2

$$\mathrm{N_{tV}} = \frac{1.5\delta}{\mathrm{a}^2} * \mathrm{K_s} * (\mathrm{K_d} + \mathrm{K_u})$$

Where:

N_{tV} is the number of structures fully burned

t is time, in minutes after initial ignition

V is wind velocity, in meters per second

δ is the degree of build-out, or building density ratio, dimensionless (Equation 9-3)

a	is the average structure plan dimension, in meters
d	is the average building separation, in meters
K_s	is half the width of the fire from flank to flank, in meters (Equation 9-5)
K_d	is the length of the fire in the downwind direction, from the initial ignition location, in meters (Equation 9-4)
K_u	is the length of the fire in the upwind (rear) direction, from the initial ignition location, in meters (Equation 9-6)

Equation 9-3

$$\delta = \left(\sum_{i=1}^{n} a_i{}^2 \right) / \text{Tract Area}$$

Where:

a_i	is plan dimension of building i
n	is number of structures

Equation 9-4

$$K_d = \frac{(a + d)}{T_d} * t$$

Equation 9-5

$$K_s = \left(\frac{a}{2} + d\right) + \frac{(a + d)}{T_s}(t - T_s) \quad ; \quad K_s \geq 0$$

Equation 9-6

$$K_u = \left(\frac{a}{2} + d\right) + \frac{(a + d)}{T_u}(t - T_u) \quad ; \quad K_u \geq 0$$

Equation 9-7

$$T_d = \frac{1}{1.6(1 + 0.1V + 0.007V^2)}\left[(1 - f_b)\left(3 + 0.375a + \frac{8d}{25 + 2.5V}\right) + f_b\left(5 + 0.5624a + \frac{16d}{25 + 2.5V}\right)\right]$$

Equation 9-8

$$T_s = \frac{1}{1 + 0.005V^2}\left[(1 - f_b)\left(3 + 0.375a + \frac{8d}{5 + 0.25V}\right) + f_b\left(5 + 0.625a + \frac{16d}{5 + 0.25V}\right)\right]$$

Equation 9-9

$$T_s = \frac{1}{1 + 0.002V^2}\left[(1 - f_b)\left(3 + 0.375a + \frac{8d}{5 + 0.2V}\right) + f_b\left(5 + 0.625a + \frac{16d}{5 + 0.2V}\right)\right]$$

Where:

f_b	is the number of fire-resistant buildings divided by the number of all buildings

A discussion of the Hamada model follows.

- It is assumed that an urban area is represented by a series of equal square (plan area) structures, with equal spacing between structures. The plan dimension of the average structure is denoted "a", and hence the plan area is a^2.
- It is assumed that the spaces between structures in a subdivision can be represented by an average separation distance, d. For purposes of this model, the separation distance represents the typical distance between structures within a single block. This distance accounts for side yards, backyards, and front yards, but does not include streets and sidewalks.
- The "degree of build-out", or building density ratio (δ) is defined by Equation 9-3. To put this building density ratio in context, a value of 0.35 represents a densely built area, and a value of 0.10 represents an area which is not very densely built.
- Figure 9-4 shows the fire spread in terms of ovals, which is the usual case of fires burning through an evenly distributed fuel load, with constant wind velocity. In actual urban conflagrations, fires exhibit this trend initially, but the final shape of the fire spread differs, through the experience of different fuel loads, as the wind shifts, and as different fire suppression actions take place. The fire burn area is approximated as the product of the downwind fire spread plus the upwind fire spread ($K_d + K_u$) times the width of the fire spread ($2K_s$).
- The fire spread model accounts for the speed of advance of the fire considering the following variables:
    - *Direction of spread*: The speed of advance of the fire is highest in the downwind direction, slower in the side wind direction, and slowest in the upwind direction.
    - *Wind velocity*: The speed of advance of the fire increases with the square of the wind velocity.
    - *Fire resistance of structures*: The speed of advance through wood structures is about twice the speed of advance through fire resistant structures.

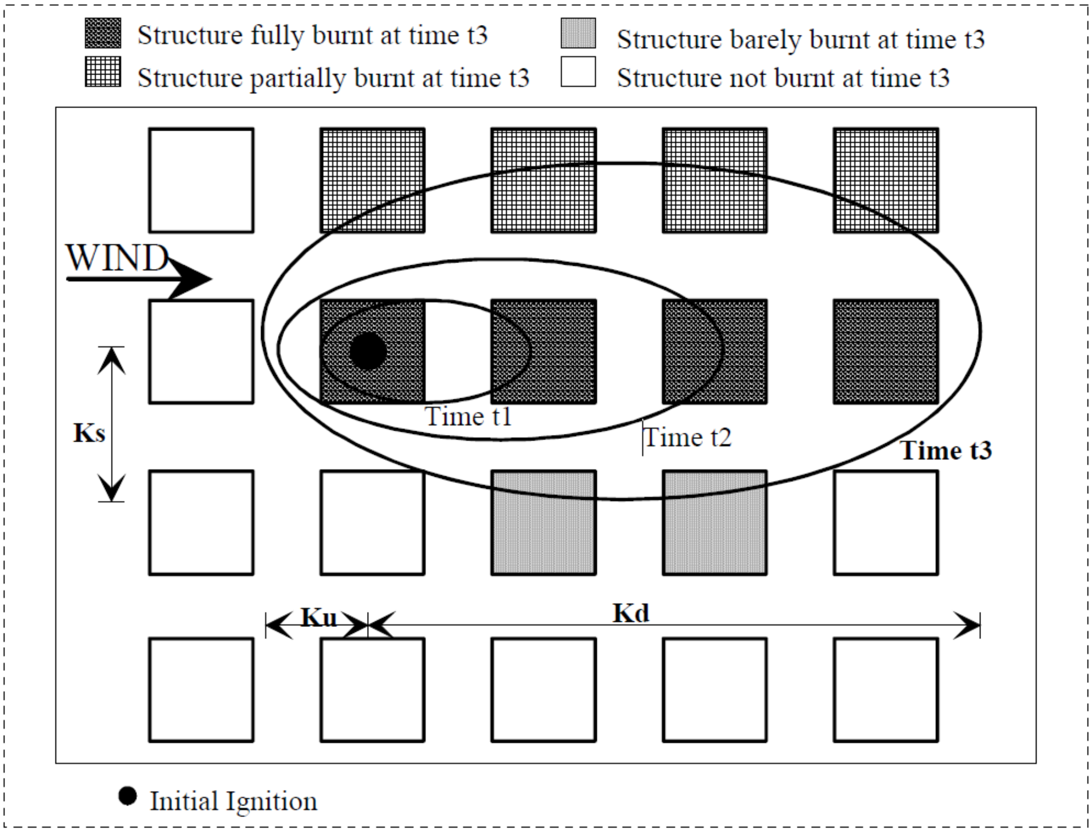


Figure 9-4 Fire Spread Process

The Hamada model results in different fire spreading rates in the downwind, sidewind, and upwind directions, even for zero wind speed. To correct this problem, a linear interpolation function is introduced which forces the fire spreading rates to be equal in all directions as the wind speed approaches zero.

For wind speeds less than 10 m/sec, the adjusted fire spreading rates (K'_d, K'_u and K'_s) are given as follows:

Equation 9-10

$$K'_d = K_d\left(\frac{V}{10}\right) + \sqrt{\left(\frac{K_d + K_u}{2}\right) K_s \left(1 - \frac{V}{10}\right)}$$

Equation 9-11

$$K'_u = K_u\left(\frac{V}{10}\right) + \sqrt{\left(\frac{K_d + K_u}{2}\right) K_s \left(1 - \frac{V}{10}\right)}$$

Equation 9-12

$$K'_s = K_s\left(\frac{V}{10}\right) + \sqrt{\left(\frac{K_d + K_u}{2}\right) K_s \left(1 - \frac{V}{10}\right)}$$

9.2.3 Suppression

The term suppression is defined as all the work of extinguishing a fire, beginning with its discovery. The steps in the suppression activity are defined as follows:

- *Discovery Time*: Elapsed time from the start of the fire until the time of the first discovery which results directly in subsequent suppression action.
- *Report Time*: Elapsed time from discovery of a fire until it is reported to a fire agency that will respond with personnel, supplies, and equipment to the fire.
- *Arrival Time*: Elapsed time from the report time until the beginning of effective work on a fire.
- *Control Time*: Elapsed time from the beginning of effective work on a fire to when the fire is controlled.
- *Mop-up Time*: Elapsed time from completion of the controlling process until enough mop-up has been done to ensure that the fire will not break out again and the structure is safe to re-occupy.

9.2.3.1 Discovery Time

The time to discover a fire is usually on the order of a few minutes if someone is present to observe the fire. In modern urban areas, many structures have smoke detectors, and these will alert occupants of the structure or people nearby that a fire has ignited. The following discovery model is used:

- 85% of structures are assumed occupied at the time of the earthquake. In these structures, fires are discovered randomly between 0 and 5 minutes.
- 15% of structures are assumed not occupied at the time of the earthquake. In these structures, fires are discovered randomly between 3 and 10 minutes.

9.2.3.2 Report Time

The time to report a fire is usually less than one minute under non-earthquake conditions. Most people report a fire directly to the fire department or call 911. The 911 dispatchers determine the degree of the emergency and notify the fire department.

After an earthquake, the process of reporting fires will be hampered, either due to phone system overload (inability to get a dial tone) or physical damage to various parts of the phone system. In theory, the fire module could account for the various levels of phone system damage using outputs from the communications system module. However, for simplification, the report time aspects are based on the following methods.

Five different methods are considered in determining how the fire will be reported to the fire department after an earthquake.

- *Cellular phone*: The report time model assumes that 15% of all fires can be reported by cellular phone, taking 1 minute.
- *Regular phone*: The model assumes that 25% of all fires can be reported by regular phone, taking 1 minute; 50% of all fires can be reported by regular phone, taking between 1 to 5 minutes; and 25% of all fires cannot be reported by regular phone.

- *Citizen alert*: In all fires, one option to report fires is for the resident to walk or drive to the nearest fire station and report the fire. This method of reporting is available for all fire ignitions. The time to report such a fire is anywhere from 1 to 11 minutes.
- *Roving Fire Vehicle*: A fire department practice for fire response after earthquakes is to immediately get fire apparatus onto the streets, looking for fires. The model assumes that a roving vehicle can detect a fire somewhere between 3 and 14 minutes after the earthquake.
- *Aircraft*: In many post-earthquake responses, helicopters and other aircraft will be flying over the affected areas. Often by the time a fire is spotted at height, it has already grown to significant proportions. The model assumes that fires can be detected by aircraft anywhere from 6 minutes to 20 minutes after the earthquake.

The module considers all five methods to report fires. The method which results in the earliest detection is the one which is used in the subsequent analysis.

9.2.3.3 Arrival Time

The arrival time is the time it takes after the fire is reported for the first fire suppression personnel and apparatus to arrive at a fire ignition. Under non-earthquake conditions, fire engines respond to fires by driving at about 30 miles per hour on average. After an earthquake, it is expected that fire engines will have a more difficult time in arriving at a fire due to damage to the road network, debris in the streets due to fallen power poles or damaged structures, traffic jams caused by signal outages, etc.

The module accounts for this slowdown in arrival time as follows:

- If the fire was detected by a roving fire engine, arrival time is 0 minutes (the engine is already at the fire).
- If the fire is called in or reported by citizens, the time for the first engine from a local fire department to arrive at the fire is between 2 and 12 minutes. (Under non-earthquake conditions, arrival time is usually about 1 to 6 minutes, so the model assumes that the fire engines will drive at 50% of normal speed).

9.2.3.4 Control Time

The time and resources needed to control the fire will depend on the status of the fire when the first fire engine arrives. The module accounts for different control times considering the status of the fire. Since the status of a fire can vary over time, the module continues to check fire status every minute.

9.2.3.4.1 Room and Contents Fires

If the total time from ignition to arrival is short, then the fire may still be a "room and contents" fire. These fires are small, and most fire engines carry enough water in the truck to control them. (Typical water carried in a pumper truck is 500 to 1,000 gallons). If this is the case, the model assumes that the first responding fire engine can control the fire. The engine is held at the location of the fire for 10 minutes. Thereafter, the engine is released for response to other fires that may be ongoing.

9.2.3.4.2 Structure Fires - Engines Needed

If the fire has spread beyond a “room and contents” fire, then suppression activities require two resources: an adequate number of personnel and fire apparatuses (engine trucks, ladder trucks, hose trucks, etc.), and an adequate amount of water.

Most fire apparatus today are engine trucks, and the Hazus FFE module does not differentiate between the capabilities of a ladder truck and an engine truck. The user should incorporate data for each fire station on the number of apparatuses housed at the station which can pump water at a rate of about 1,000 to 2,000 gpm. Hose tenders without pumps, search and rescue trucks, and automobiles are not counted as available apparatuses in the module.

The module determines the number of required trucks as follows:

- Single-Family Residential Fires: Figure 9-5 shows the number of fire trucks needed to suppress a fire, versus the number of structures already burned.
- Other Fires: Figure 9 6 shows the number of fire trucks needed to suppress a fire, versus the number of structures already burned, for the case when the original ignition occurs at a structure other than a single-family home. These ignitions include fires at apartment, commercial, wholesale, and industrial structures. From Figure 9-6, it can be seen that a minimum of two trucks are needed if there are four or fewer burnt structures. Since only one truck is sent to each fire, this can lead to all fires becoming a conflagration, regardless of size. Accordingly, the model assumes the following:
    - One truck is needed if the number of burnt structures is less than 2.
    - Two trucks are needed if the number of burnt structures is between 2 and 4

This assumption will reduce the total burnt area since all fires close to the fire stations will be controlled and put out by only one engine.

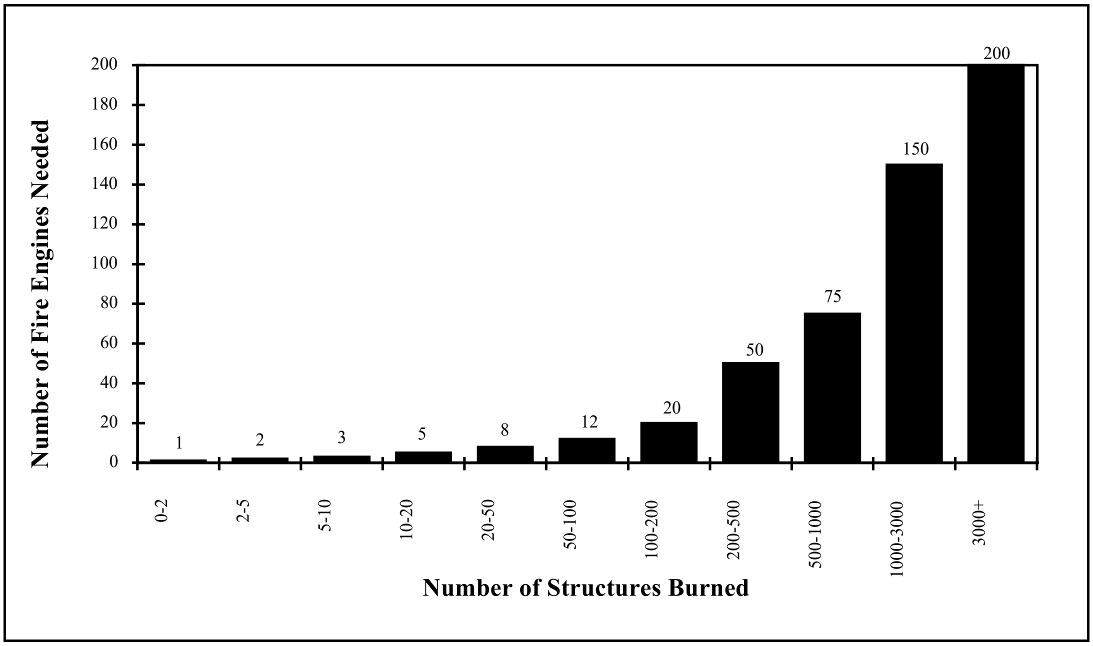


Figure 9-5 Number of Engines Needed for Ignitions that Start in Single-Family Homes

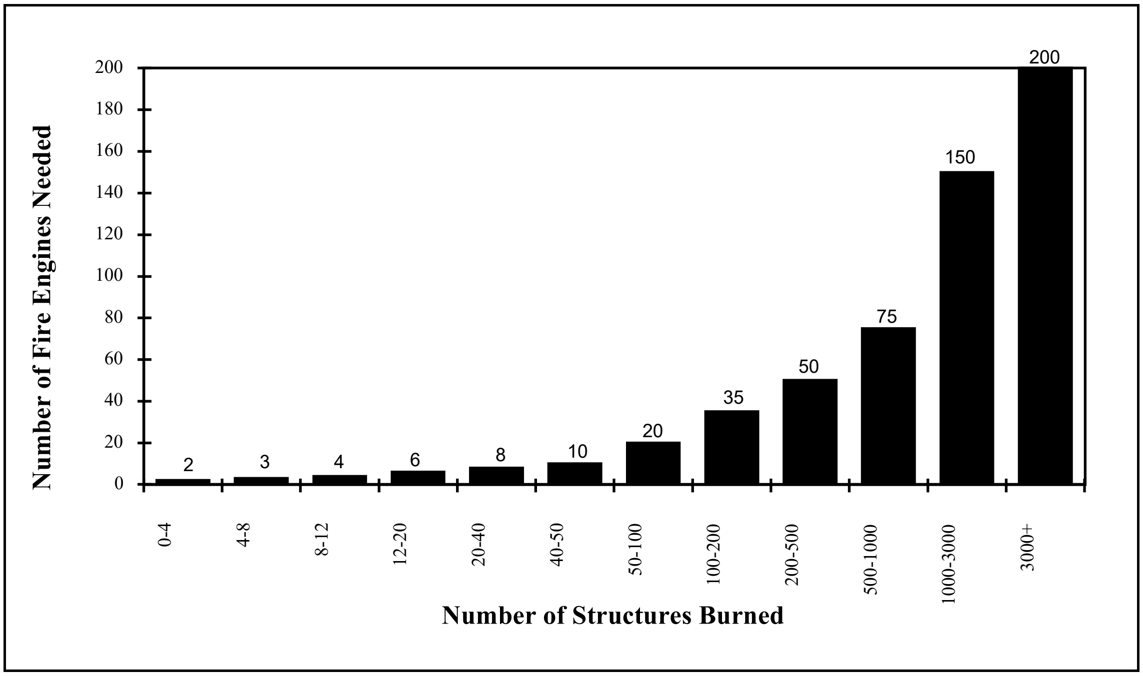


Figure 9-6 Number of Engines Needed for Ignitions that Start in Structures Other than Single-Family Homes

9.2.3.4.3 Structure Fires - Water Needed

Except in the case of “room and content” fires, urban fire suppression usually requires large quantities of water in order to gain control. (The issue of firebreaks in urban areas is described later). The amount of water needed is usually expressed in two terms:

- *Required Flow*: This is the amount of water needed to fight a fire from one or more fire hydrants, usually expressed in gallons per minute, or gpm.
- *Required Duration*: This is the length of time the fire flow is needed, in hours (or minutes).

A term often used in describing water needs is pressure. In typical fire-fighting terminology, the fire flows are required at the hydrant outlet at a minimum of 20 pounds per square inch (psi) residual pressure while the hydrant is flowing.

Most cities use a water distribution system that delivers water for customer needs (drinking, sanitary, and other uses) and water for fire flow needs through a single set of pipes. Water pressures are usually kept at around 40 psi - 60 psi in the mains to meet normal customer needs. When a hydrant is opened, flows through the water mains increase. In areas of the city where mains are not highly interconnected (such as in hillside communities) or where mains have small diameters (2", 4", and some 6" pipes), the high velocities of water needed to deliver the water to the fire hydrant can cause significant pressure drops. If the water pressure drops below about 20 psi, fire engines have a difficult time drafting the water out of the hydrant.

The water needed to fight a fire at any given time t (W_t, in gallons), depends upon the extent of the fire. The following equations are used to calculate the water needed:

Equation 9-13

$$W_t = 1250(N_{tV})^{0.4} \quad ; \quad 0 < N_{tV} \le 3000$$

Where:

N_{tV} is the number of structures burned at time t, at wind velocity V

Equation 9-13 is based upon the Uniform Fire Code (ICBO, 1991) for single structure fires (N_{tV} = 1), modified for large conflagration fires.

For apartment fires, the amount of water needed is somewhat higher than the water needed for a single-family residence, and is expressed in Equation 9-14 and Equation 9-15.

Equation 9-14

$$W_t = 1500(N_{tV})^{0.5} \quad ; \quad 0 < N_{tV} \leq 4$$

Equation 9-15

$$W_t = 3000 + 1250(N_{tV} - 4)^{0.4} \quad ; \quad 4 < N_{tV} \leq 3000$$

For commercial, wholesale, and industrial fires, the amount of water needed is higher than the water needed for a small apartment building, and is expressed in Equation 9-16 and Equation 9-17.

Equation 9-16

$$W_t = 2500(N_{tV})^{0.5} \quad ; \quad 0 < N_{tV} \leq 4$$

Equation 9-17

$$W_t = 5000 + 1250(N_{tV} - 4)^{0.4} \quad ; \quad 4 < N_{tV} \leq 3000$$

For petroleum fires, the amount of water needed is higher than the water needed for other types of fires, and is expressed in Equation 9-18 and Equation 9-19.

Equation 9-18

$$W_t = 4000(N_{tV})^{0.5} \quad ; \quad 0 < N_{tV} \leq 4$$

Equation 9-19

$$W_t = 8000 + 1250(N_{tV} - 4)^{0.4} \quad ; \quad 4 < N_{tV} \leq 3000$$

For all types of fires, the duration of flow is determined by Equation 9-20:

Equation 9-20

$$D = 0.5 * (\text{engines needed})^{0.4}$$

Where:

D	is the duration of flow needed, in hours
(engines needed)	is taken from Figure 9-5 or Figure 9-6

9.2.3.4.4 Engines Available

The number of fire apparatuses (engines and ladders) available in the study area is supplied by the user as input to the module.

The module tracks fire detection order. Fire engines will serve fires that have been discovered first and are nearest to the fire stations. An insufficient number of fire trucks will result in the fire spreading faster, which is addressed in Section 9.2.3.4.7.

9.2.3.4.5 Water Available

The water available to fight a fire depends upon the capacity of the water distribution system, taking into account the level of damage to the system. The amount of water available in a cell to suppress fires includes the following parameters:

- Available water flow
- Duration of water flow for a pumped water system

9.2.3.4.6 Fire Spread with Partially Effective Suppression

For each fire, at each time step of the analysis, the module checks the available water flow for fire suppression activities and the number of fire trucks at the scene of the fire. Based upon the size of the fire at that time, the module calculates the number of fire trucks needed and the amount of water normally needed to control the fire.

From these values, two ratios are calculated, as shown in Equation 9-21 and Equation 9-22:

Equation 9-21

$$\mathrm{R_{truck}} = \frac{\text{trucks at fire}}{\text{trucks needed at fire}} \quad ; \quad \mathrm{R_{truck}} \leq 1.0$$

Equation 9-22

$$\mathrm{R_{water}} = \frac{\text{available flow at fire}}{\text{flow needed at fire}} \quad ; \quad \mathrm{R_{water}} \leq 1.0$$

Where:

Equation 9-23

$$\begin{aligned}&\text{available flow at fire}\\&\quad = (\text{reduction factor}) * (\text{typical discharge from hydrant})\\&\quad * (\text{number of hydrants to fight fire})\end{aligned}$$

The reduction factor is set to the serviceability index obtained from the water system performance assessment (see Section 8.1.7). The typical discharge from a hydrant is around 1750 gallons/minute. Finally, the number of hydrants available at the scene of the fire is estimated as given in Equation 9-24:

Equation 9-24

$$\text{No. of Hydrants} = \frac{1.5 * (\mathrm{K_d} + \mathrm{K_u}) * (2\mathrm{K_s})}{(100 * 100)}$$

Where:

K_d, K_u, and K_s are as previously defined. Note that 100 is the average spacing in meters between fire hydrants (typically, the spacing is in the range 60 m to 150 m). The coefficient 1.5 reflects the assumption of 50% of additional fire hydrants from adjacent blocks or equivalent will be available to fight the fire.

Based on the calculated values of R_{truck} and R_{water}, the fire suppression effectiveness is calculated using Equation 9-25.

Equation 9-25

$$\mathrm{P_{effective}} = (\mathrm{R_{truck}} * \mathrm{R_{water}})^{0.7} \geq 0.33\mathrm{R_{truck}}$$

This equation reflects the following logic: if the available trucks and water are much less than required, then there is good chance that the fire will spread. Conversely, if most of the trucks and water needed are available, then the fire suppression effectiveness improves.

Due to fire suppression, the rate of fire spread will be slowed and the reduced spread rate is estimated using Equation 9-26.

Equation 9-26

$$\text{Spread Rate} = \text{Spread}_{\text{non-suppressed}} * \left(1.0 - \mathrm{P_{effective}^{0.7}}\right)$$

The Spread Rate is the key variable used in determining the spread of the fire. Equation 9-25 and Equation 9-26 together provide the prediction as to the effectiveness of partial fire suppression in stopping urban conflagration.

9.2.3.4.7 Fire Spread at Natural Fire Breaks

Fire breaks are one of the mechanisms that stop fires from spreading. Fire breaks abound in an urban area and include streets, highways, parks, and lakes. The module accounts for fire breaks as follows:

- Fires can spread within a city block following Equation 9-3 through Equation 9-9, as modified by Equation 9-26. The module keeps track of the spread.
- The average city block is assumed to have two rows of houses, and there are 15 houses down a single side of a block. The average length of a city block is taken as the average of the width and length of the block, using a default width of 25 meters.
- The model assumes that every fifth fire break is three times wider than the average city street fire break. These wide fire breaks account for the presence of wide boulevards, interstate highways, parks, and lakes.

If the fire spread just reaches a fire break, then there is a probability that the fire break will control the fire, even with no active suppression or partial suppression ongoing. The probability of the fire jumping the fire break increases with the wind velocity, decreases with the width of the fire break, and decreases if there is active fire suppression as shown in Figure 9-7. Figure 9-7 is adapted from Scawthorn (1987) and combined with subject matter expertise.

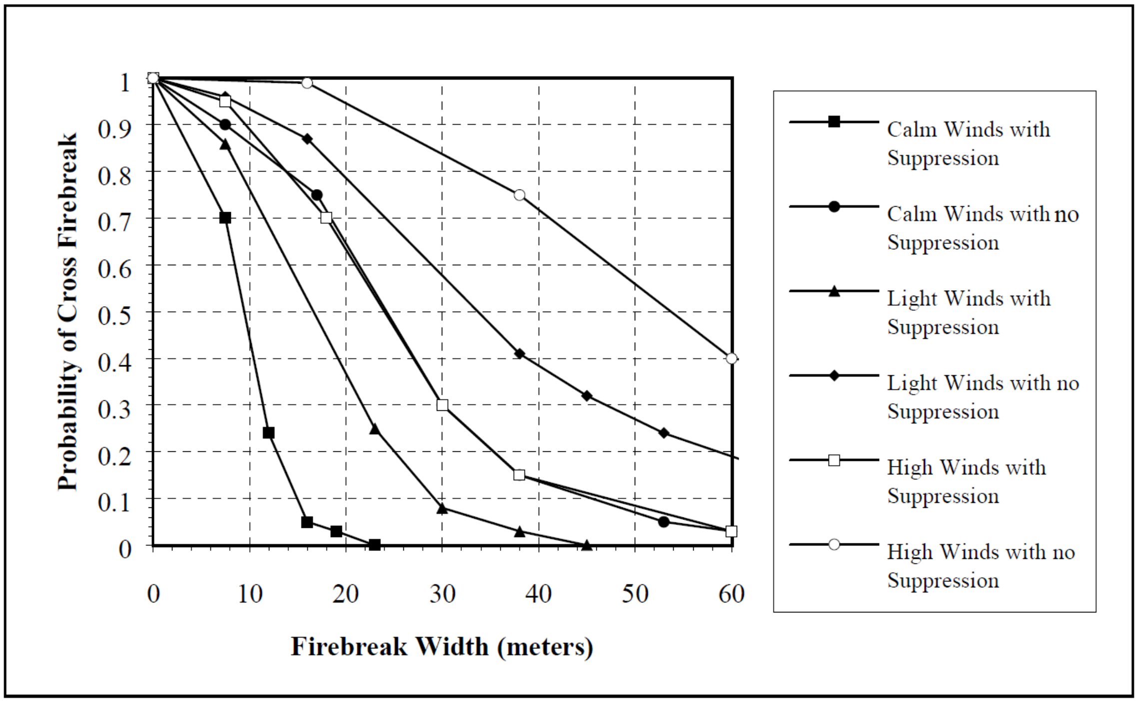


Figure 9-7 Probability of Crossing a Firebreak

Section 10. Induced Damage Modules – Debris

Very little research has been done in the area of estimating debris amounts from earthquakes. Some of the early regional loss estimation studies (e.g., Algermissen et al., 1973; Rogers et al., 1976) included simplified models for estimating the amount of debris from shaking damage to unreinforced masonry structures. This methodology adopts a similar empirical approach to estimate quantities of two different types of debris. The first is debris that falls in large pieces, such as steel members or reinforced concrete elements. These require special treatment to break into smaller pieces before they are hauled away. The second type of debris is smaller and easily moved with bulldozers, other machinery and tools. This includes brick, wood, glass, and other materials.

10.1 Scope

The debris module only estimates debris from building damage during earthquakes. No debris estimates are made for bridges or other transportation or utility system facilities.

10.1.1 Form of Damage Estimates

The debris module determines the expected amounts of debris generated in each Census tract. Output from this module is the weight of debris by type of material, in tons. The types of debris are defined as follows:

- Light debris - brick, wood, and other debris
- Heavy debris - reinforced concrete and steel members

10.1.2 Input Requirements

Input to this module includes the following items:

- Probabilities of structural and nonstructural damage states for specific building types for each Census tract, provided from the direct physical damage module
- Square footage by occupancy class for each Census tract provided from the general building stock inventory
- The occupancy to specific building type relationship for each Census tract

10.2 Description of Methodology

The methodology for debris estimation is based on an empirical approach. That is, given the damage states for structural and nonstructural components, debris estimates are based on observations of damage that has occurred in past earthquakes and estimates of the weights of structural and nonstructural elements. The estimates are made considering specific building type. Tables have been compiled to estimate the amount of debris generated from different structural and nonstructural damage states for each specific building type.

Debris generated from damaged buildings (in tons) is based on the following factors:

- Unit weight of structural and nonstructural elements (tons per 1,000 sq. ft. of floor area) for each of the specific building types

- Damage state probabilities for both structural and drift-sensitive nonstructural elements by Census tract
- Square footage of each of the specific building types by Census tract
- Debris generated from different damage states of structural and nonstructural elements (% of unit weight of element)

The default values for unit weights of structural and nonstructural elements are given in Table 10-1, and debris generated (% of weight) per specific building type and damage state are given in Table 10-2 for light debris and in Table 10-3 for heavy debris.

Table 10-1 Unit Weight (in tons per 1,000 ft.^{2}) for Structural and Nonstructural Elements by Specific building type

#	Specific Building Type	Brick, Wood and Other		Reinforced Concrete and Steel	
		Structural	Nonstructural	Structural	Nonstructural
1	W1	6.5	12.1	15.0	0.0
2	W2	4.0	8.1	15.0	1.0
3	S1L	0.0	5.3	44.0	5.0
4	S1M	0.0	5.3	44.0	5.0
5	S1H	0.0	5.3	44.0	5.0
6	S2L	0.0	5.3	44.0	5.0
7	S2M	0.0	5.3	44.0	5.0
8	S2H	0.0	5.3	44.0	5.0
9	S3	0.0	0.0	67.0	1.5
10	S4L	0.0	5.3	65.0	4.0
11	S4M	0.0	5.3	65.0	4.0
12	S4H	0.0	5.3	65.0	4.0
13	S5L	20.0	5.3	45.0	4.0
14	S5M	20.0	5.3	45.0	4.0
15	S5H	20.0	5.3	45.0	4.0
16	C1L	0.0	5.3	98.0	4.0
17	C1M	0.0	5.3	98.0	4.0
18	C1H	0.0	5.3	98.0	4.0
19	C2L	0.0	5.3	112.0	4.0
20	C2M	0.0	5.3	112.0	4.0
21	C2H	0.0	5.3	112.0	4.0
22	C3L	20.0	5.3	90.0	4.0
23	C3M	20.0	5.3	90.0	4.0
24	C3H	20.0	5.3	90.0	4.0
25	PC1	5.5	5.3	40.0	1.5
26	PC2L	0.0	5.3	100.0	4.0
27	PC2M	0.0	5.3	100.0	4.0
28	PC2H	0.0	5.3	100.0	4.0

#	Specific Building Type	Brick, Wood and Other		Reinforced Concrete and Steel	
		Structural	Nonstructural	Structural	Nonstructural
29	RM1L	17.5	5.3	28.0	4.0
30	RM1M	17.5	5.3	28.0	4.0
31	RM2L	17.5	5.3	78.0	4.0
32	RM2M	24.5	5.3	78.0	4.0
33	RM2H	24.5	5.3	78.0	4.0
34	URML	35.0	10.5	41.0	4.0
35	URMM	35.0	10.5	41.0	4.0
36	MH	10.0	18.0	22.0	0.0

Table 10-2 Brick, Wood, and Other Debris Generated from Damaged Structural and Nonstructural Elements (in Percent of Weight)

#	Specific Building Type	Structural Damage State				Nonstructural Damage State			
		Slight	Moderate	Extensive	Complete	Slight	Moderate	Extensive	Complete
1	W1	0	5	34	100	2	8	35	100
2	W2	0	6	33	100	2	10	40	100
3	S1L	0	0	0	100	1	7	35	100
4	S1M	0	0	0	100	1	7	35	100
5	S1H	0	0	0	100	1	7	35	100
6	S2L	0	0	0	100	0	0	0	100
7	S2M	0	0	0	100	0	0	0	100
8	S2H	0	0	0	100	0	0	0	100
9	S3	0	0	0	100	0	0	0	100
10	S4L	0	0	0	100	1	7	35	100
11	S4M	0	0	0	100	1	7	35	100
12	S4H	0	0	0	100	1	7	35	100
13	S5L	5	25	60	100	1	7	35	100
14	S5M	5	25	60	100	1	7	35	100
15	S5H	5	25	60	100	1	7	35	100
16	C1L	0	0	0	100	1	7	35	100
17	C1M	0	0	0	100	1	7	35	100
18	C1H	0	0	0	100	1	7	35	100
19	C2L	0	0	0	100	1	7	35	100
20	C2M	0	0	0	100	1	7	35	100
21	C2H	0	0	0	100	1	7	35	100
22	C3L	5	25	60	100	1	7	35	100
23	C3M	5	25	60	100	1	7	35	100
24	C3H	5	25	60	100	1	7	35	100
25	PC1	0	6	32	100	2	11	42	100

#	Specific Building Type	Structural Damage State				Nonstructural Damage State			
		Slight	Moderate	Extensive	Complete	Slight	Moderate	Extensive	Complete
26	PC2L	0	0	0	100	1	7	35	100
27	PC2M	0	0	0	100	1	7	35	100
28	PC2H	0	0	0	100	1	7	35	100
29	RM1L	4	20	50	100	2	10	40	100
30	RM1M	4	20	50	100	2	10	40	100
31	RM2L	5	25	60	100	1	7	35	100
32	RM2M	5	25	60	100	1	7	35	100
33	RM2H	5	25	60	100	1	7	35	100
34	URML	5	25	55	100	2	12	45	100
35	URMM	5	25	55	100	2	12	45	100
36	MH	0	5	33	100	2	8	35	100

Table 10-3 Reinforced Concrete and Steel Debris Generated from Damaged Structural and Nonstructural Elements (in Percent of Weight)

#	Specific Building Type	Structural Damage State				Nonstructural Damage State			
		Slight	Moderate	Extensive	Complete	Slight	Moderate	Extensive	Complete
1	W1	0	3	27	100	0	0	0	100
2	W2	0	2	25	100	0	10	28	100
3	S1L	0	4	30	100	0	8	28	100
4	S1M	0	4	30	100	0	8	28	100
5	S1H	0	4	30	100	0	8	28	100
6	S2L	0	4	30	100	0	8	28	100
7	S2M	0	4	30	100	0	8	28	100
8	S2H	0	4	30	100	0	8	28	100
9	S3	0	5	30	100	0	10	30	100
10	S4L	2	10	40	100	0	10	30	100
11	S4M	2	10	40	100	0	10	30	100
12	S4H	2	10	40	100	0	10	30	100
13	S5L	0	4	30	100	0	10	30	100
14	S5M	0	4	30	100	0	10	30	100
15	S5H	0	4	30	100	0	10	30	100
16	C1L	0	5	33	100	0	8	28	100
17	C1M	0	5	33	100	0	8	28	100
18	C1H	0	5	33	100	0	8	28	100
19	C2L	1	8	35	100	0	10	30	100
20	C2M	1	8	35	100	0	10	30	100
21	C2H	1	8	35.	100	0	10	30	100

#	Specific Building Type	Structural Damage State				Nonstructural Damage State			
		Slight	Moderate	Extensive	Complete	Slight	Moderate	Extensive	Complete
22	C3L	0	4	32	100	0	10	30	100
23	C3M	0	4	32	100	0	10	30	100
24	C3H	0	4	32	100	0	10	30	100
25	PC1	2	10	35	100	0	10	30	100
26	PC2L	2	7	35	100	0	9	30	100
27	PC2M	2	7	35	100	0	9	30	100
28	PC2H	2	7	35	100	0	9	30	100
29	RM1L	0	3	25	100	0	10	30	100
30	RM1M	0	3	26	100	0	10	31	100
31	RM2L	0	3	31	100	0	9	30	100
32	RM2M	0	3	31	100	0	9	30	100
33	RM2H	0	3	31	100	0	9	30	100
34	URML	0	2	25	100	0	10	29	100
35	URMM	0	2	25	100	0	10	29	100
36	MH	0	3	27	100	0	0	0	100

The following notation is used throughout this Section:

i is the iteration variable for the types of debris, i = 1 to 2

Where:

i = 1 for brick, wood, and other

i = 2 for reinforced concrete and steel components

j is the iteration variable for the damage states, j = 1 to 5,

Where:

j = 1 for damage state None

j = 2 for damage state Slight

j = 3 for damage state Moderate

j = 4 for damage state Extensive

j = 5 for damage state Complete

k is the iteration variable for the Specific Building Types, k = 1 to 36 (see Table 5-1)

The inputs provided from the direct physical damage module are the probabilities of different structural and nonstructural Damage States. Thus, the first step in the debris calculation is to combine the debris fraction generated from the different Damage States into the expected debris fraction for each Specific Building Type.

The expected debris fraction for Specific Building Type k and Debris type i due to structural damage is given by:

Equation 10-1

$$\mathrm{EDF_s(i,k)} = \sum_{\mathrm{j}=2}^{5} \mathrm{P_s(j,k)} * \mathrm{DF_s(i,j,k)}$$

Where:

$\mathrm{EDF_s(i,k)}$	is the expected debris fraction of Debris Type i due to structural damage for Specific Building Type k
$\mathrm{P_s(j,k)}$	is the probability of structural damage state, j, for Specific Building Type k at the location being considered
$\mathrm{DF_s(i,j,k)}$	is the debris fraction of debris type i for Specific Building Type k in structural damage state j (from Table 10-2 and Table 10-3)

The expected debris fraction for Specific Building Type k and Debris Type i due to nonstructural damage is given by:

Equation 10-2

$$\mathrm{EDF_{ns}(i,k)} = \sum_{\mathrm{j}=2}^{5} \mathrm{P_{ns}(j,k)} * \mathrm{DF_{ns}(i,j,k)}$$

Where:

$\mathrm{EDF_{ns}(i,k)}$	is the expected debris fraction of Debris Type i due to nonstructural damage for Specific Building Type k
$\mathrm{P_{ns}(j,k)}$	is the probability of drift sensitive nonstructural damage state j for Specific Building Type k at the location being considered
$\mathrm{DF_{ns}(i,j,k)}$	is the debris fraction of Debris Type i for Specific Building Type k in drift sensitive nonstructural damage state, j (from Table 10 2 and Table 10 3)

These values indicate the expected percentage of Debris Type i, generated due to structural or nonstructural damage to Specific Building Type k.

If the square footage of each Specific Building Type (by Census tract) is known, SQ(k), as are the weights of Debris Type i per 1,000 square feet of building, W_s(i,k) and W_{ns}(i,k), then the amount of debris for this particular location can be obtained as follows:

Equation 10-3

$$DB(i) = \sum_{k=1}^{36} [EDF_s(i,k) * W_s(i,k) + EDF_{ns}(i,k) * W_{ns}(i,k)] * SQ(k)$$

Where:

$W_s(i,k)$	is the weight of Debris Type i, in tons per 1,000 sq. ft. of floor area, for structural elements of Specific Building Type k (from Table 10 1)
$W_{ns}(i,k)$	is the weight of Debris Type i, in tons per 1,000 sq. ft. of floor area, for nonstructural elements of Specific Building Type k (from Table 10 1)
SQ(k)	is the Census tract square footage for Specific Building Type k, in thousands of square feet
DB(i)	is the amount of Debris Type, i (in tons)

Section 11. Direct Economic Losses

This section describes the conversion of damage state information, developed in previous modules, into estimates of dollar loss. Discussion of the underlying replacement cost and other economic parameters can be found in the *Hazus Inventory Technical Manual*.

The methodology provides estimates of the structural and nonstructural repair costs resulting from building damage and the associated loss of building contents and business inventory. Building damage can also result in additional losses by restricting the building's ability to function properly. To account for this, direct business interruption and rental income losses are estimated. These losses are calculated from the building damage estimates using methods described later.

The costs of building repair and replacement are frequently required outputs of a loss estimation study. The additional estimates of consequential losses give an indication of the immediate impacts this building damage can have on the community. Such impacts can include financial consequences to the community's businesses due to direct businesses interruption, an increased need for financial resources to repair the damage, and potential housing losses.

In strict economic terms, buildings, their inventories, and public infrastructure represent capital investments that produce income. The value of a building and its inventory is determined by the capitalized value of the income produced by the initial investment that created the building or inventory. If the dollar value of the damaged buildings is estimated, and then the income lost from the absence of the functioning facilities is added, indirect economic loss may be overestimated (Section 14). However, for the assessment of direct economic loss, the losses can be estimated and evaluated independently.

Since a significant use for loss estimation studies is to provide input for future benefit-cost studies used to evaluate mitigation strategies, the list of consequential losses considered here is similar to those developed for the FEMA benefit-cost procedure described in FEMA publications 227 and 228 (FEMA, 1992a, b), and 255 and 256 (FEMA, 1994a, b). This procedure is limited to conventional real-estate parameters similar to those used in evaluating the feasibility of a development project and does not attempt to evaluate the full range of socio-economic impacts that might follow specific mitigation strategies.

Even though the derivation of consequential losses represents a significant expansion of the normal consideration of building damage/loss, this particular methodology is still limited in its consideration of economic loss to those that can be directly derived from building and infrastructure damage and lend themselves to ready conversion from damage to dollars. The real socio-economic picture is much more complex. Economic impacts may have major societal effects on individuals or discrete population groups and there may be social impacts that ultimately manifest themselves in economic consequences. In many cases the linkages are hard to trace with accuracy and the effects are difficult to quantify because definite systematic data is lacking.

For example, the closing of the Oakland/San Francisco Bay Bridge for 30 days following the 1989 Loma Prieta earthquake required approximately a quarter of a million daily users of the bridge to rearrange their travel patterns. Many individual commuters were forced to take a significantly longer and more costly route to their destinations. At the same time, other commuters changed to use of the BART rail system or bus services, which also altered their family expenditure patterns. Lengthier trips for business service travelers and material suppliers resulted in varying degrees of loss of productivity. Businesses directly related to normal operation of the bridge, such as gas stations and automobile repair shops on the approach routes to the bridge suffered losses.

Repairs to the bridge represented a direct cost to the state budget. At the same time, the revenues from bridge tolls were nonexistent. However, some businesses gained from closure: some gas stations had improved business and revenues to other bridges, the BART system, and bus companies increased. Increased commuting time resulted in loss of leisure and family time and shifts in the customer and sales patterns of many small businesses, resulted in an increase in normal business worries.

If this 30-day loss of function had instead lasted for a period of years (as is the case for other elements of the Bay Area Freeway system) the socio-economic impacts would have been profound and long lasting throughout the Bay region.

This example suggests the range of inter-related consequential impacts that could stem from damage to a single structure. These impacts were also accompanied by a host of other impacts to individuals, businesses, institutions, and communities that serve to increase the complexity of post-earthquake effects. As understanding is gained of these interactions and data collection becomes richer and more systematic, quantification of the consequential losses of earthquake damage can become broader and more accurate.

11.1 Scope

Given the complexity of the problem and present scarcity of data, the methodology focuses on a few key issues that are of critical importance to government and the community, that can be quantified with reasonable assurance, and provide a picture of the cost consequences of building and infrastructure damage. In addition, application of the methodology will provide information that would be useful in a more detailed study of a particular economic or social sector, such as impact on housing stock or on a significant local industry. Finally, the structure of the methodology should be of assistance in future data gathering efforts.

While the links between this module and the previous modules dealing with damage are direct and the derivations are transparent, the links between this module and the indirect economic loss module (IELM, Section 14), are less clear. While some of the estimates derived in this module (e.g., loss of income by sector, building repair costs, and the loss of contents and inventories) may be imported directly into the IELM, some interpretation of the direct economic loss estimates would be necessary for a more detailed indirect economic loss study. For example, it would be necessary to translate the repair times and costs derived in this module to monthly reconstruction investment estimates for use in a longer-term indirect loss estimate.

This section provides descriptions of the methodologies used to estimate direct economic loss, as derived from estimates of building and utility and transportation systems damage. As noted above, the underlying replacement cost model and economic data are described in more detail in the *Hazus Inventory Technical Manual*. Methods for calculating the following dollar losses are provided:

- Building repair costs
- Building contents losses
- Building inventory losses

In order to enable time dependent losses to be calculated, default models are provided for:

- Building recovery time and loss of function (business interruption) time

Procedures for calculating the following time-dependent losses are also provided:

- Relocation expenses
- Income loss (also referred to as loss of proprietors' income)
- Rental income losses
- Wage losses

For each utility and transportation system component, information is provided on assumed numerical damage ratios corresponding to damage states (replacement values are discussed in the *Hazus Inventory Technical Manual*). Section 7 and Section 8 provide restoration curves corresponding to utility and transportation system damage states. With this information, the cost of damage to utility and transportation systems and the elapsed time for their restoration are calculated. However, no attempt is made to estimate losses due to interruption of customer service, alternative supply services, and other similar measures.

Dollar losses due to post-earthquake fire are not explicitly addressed. A value for building losses from fire can be estimated by relating the area of fire spread to the volume of construction and the associated replacement cost. The nature of the fire-induced damage states (which would vary from those of ground shaking damage) are not developed, and estimates of dollar loss from these causes should be regarded as very broad estimates. Additionally, the possibility of double counting of damage is present. More specific studies should be undertaken if the user believes that post-earthquake fire might represent a serious risk.

Since the methodology goes no further than indicating sources of hazardous materials, no methodology is provided for estimating losses due to the release of such materials. If the possibility of serious losses from hazardous materials release is a matter of concern, specific studies should be undertaken.

11.1.1 Form of Direct Economic Loss Estimates

Direct economic loss estimates are provided in dollars. For a complete description of the current Hazus replacement cost models, the user is referred to the *Hazus Inventory Technical Manual*.

11.1.2 Input Requirements

In general, input data for direct economic losses consists of building damage estimates from the direct physical damage module. The damage estimates are in the form of probabilities of being in each damage state, for each structural type or occupancy class. The structural classification system is as discussed in Section 5.3. The Hazus Occupancy classes, for which replacement cost data are provided, are listed in Table 11-1 and described in detail in the *Hazus Inventory Technical Manual*. Damage state probabilities are provided from the direct physical damage module for both structural and nonstructural damage. These damage state probabilities are then converted to monetary losses using inventory information and economic data.

The types of economic data include building repair and replacement costs, contents value for different occupancies, annual gross sales by occupancy, and relocation expenses and income by occupancy. While baseline values are provided for these data (see the *Hazus Inventory Technical Manual* for more detail), the user may wish to utilize more accurate local values.

Direct economic loss estimates for transportation and utility systems are limited to the cost of repairing damage to the utility and transportation systems. Baseline values are provided for replacement values of utility and transportation system components as a guide. It is expected that in a Level 2 Analysis with user-supplied inventory data (see Section 2.3.2), the user will input more accurate replacement values based on local expert input or knowledge of utility and transportation system values in the region.

Table 11-1 Hazus Occupancy Classes

No.	Category	Label	Occupancy Class	Description
1	Residential	RES1	Single-family Dwelling	Detached House
2	Residential	RES2	Mobile Home	Mobile Home
3 - 8	Residential	RES3A-F	Multi-family Dwelling	Apartment/Condominium
9	Residential	RES4	Temporary Lodging	Hotel/Motel
10	Residential	RES5	Institutional Dormitory	Group Housing (military, college), Jails
11	Residential	RES6	Nursing Home	
12	Commercial	COM1	Retail Trade	Store
13	Commercial	COM2	Wholesale Trade	Warehouse
14	Commercial	COM3	Personal and Repair Services	Service Station/Shop
15	Commercial	COM4	Professional/Technical Services	Offices
16	Commercial	COM5	Banks/Financial Institutions	
17	Commercial	COM6	Hospital	
18	Commercial	COM7	Medical Office/Clinic	Offices
19	Commercial	COM8	Entertainment & Recreation	Restaurants/Bars
20	Commercial	COM9	Theaters	Theaters
21	Commercial	COM10	Parking	Garages
22	Industrial	IND1	Heavy	Factory
23	Industrial	IND2	Light	Factory
24	Industrial	IND3	Food/Drugs/Chemicals	Factory
25	Industrial	IND4	Metals/Minerals Processing	Factory
26	Industrial	IND5	High Technology	Factory
27	Industrial	IND6	Construction	Office
28	Agriculture	AGR1	Agriculture	
29	Religion/ Non-Profit	REL1	Church	
30	Government	GOV1	General Services	Office
31	Government	GOV2	Emergency Response	Police/Fire Station
32	Education	EDU1	Schools	
33	Education	EDU2	Colleges/Universities	Does not include group housing

11.2 Description of Methodology: Buildings

This section describes the estimation of building damage-related direct economic losses.

11.2.1 Building Repair Costs

To establish dollar loss estimates, the building's damage state probabilities must be converted to dollar loss equivalents. Losses will be due to both structural and nonstructural damage. For a given occupancy and damage state, building repair costs are estimated as the product of the floor area of each building type within the given occupancy, the probability of the building type being in the given damage state, and repair costs of the building type per square foot for the given damage state (expressed relative to replacement cost), summed over all building types within the occupancy.

Some methodologies suggest that the true cost of buildings damaged or destroyed is their loss of market value, reflecting the age of the building, depreciation, and similar attributes. Replacement value is a frequently requested output of a loss estimation study because it gives an immediate, understandable picture of the community building losses and disaster assistance is currently granted based on replacement value. However, market value is not constant in relation to replacement value. For example, typical estimates of market value include the value of the lot: in locations of high land cost, market value may greatly exceed the building replacement value (which excludes lot value). Building age does not necessarily result in a linear loss of market value. After a certain age some buildings begin to acquire additional value by virtue of architectural style and craftsmanship and true replacement cost might greatly exceed market value.

These issues may need to be considered in a detailed evaluation of the direct economic losses where specific building inventories or economic aspects of the damage are being evaluated. Full discussion of these and other related issues may be found in Howe and Cochrane (1993).

For structural damage, losses are calculated as follows:

Equation 11-1

$$\mathrm{CS_{ds,i}} = \mathrm{BRC_i} * \sum_{\mathrm{i}=1}^{33} \mathrm{PMBTSTR_{ds,i}} * \mathrm{RCS_{ds,i}}$$

Equation 11-2

$$\mathrm{CS_i} = \sum_{\mathrm{ds}=2}^{5} \mathrm{CS_{ds,i}}$$

Where:

$\mathrm{CS_{ds,i}}$	is the cost of structural damage (repair costs) for damage state ds, and occupancy class i
$\mathrm{BRC_i}$	is the building replacement cost of occupancy class i, as described in the *Hazus Inventory Technical Manual*
$\mathrm{PMBTSTR_{ds,i}}$	is the probability of occupancy class i, being in structural damage state ds (see Section 5)
$\mathrm{RCS_{ds,i}}$	is the structural repair cost ratio (in % of building replacement cost) for occupancy class, I, in damage state, ds (Table 11-2)

Table 11-2 shows the baseline values for the structural repair cost ratio for each damage state and occupancy classification. The relative percentage of total building cost allocated to structural and nonstructural components is derived from the replacement cost model component costs for each occupancy class (for more information, refer to the *Hazus Inventory Technical Manual*).

Table 11-2 Structural Repair Cost Ratios (in % of building replacement cost)

No.	Label	Occupancy Class	Structural Damage State			
			Slight	Moderate	Extensive	Complete
1	RES1	Single-family Dwelling	0.5	2.3	11.7	23.4
2	RES2	Mobile Home	0.4	2.4	7.3	24.4
3-8	RES3A-F	Multi-family Dwelling	0.3	1.4	6.9	13.8
9	RES4	Temporary Lodging	0.2	1.4	6.8	13.6
10	RES5	Institutional Dormitory	0.4	1.9	9.4	18.8
11	RES6	Nursing Home	0.4	1.8	9.2	18.4
12	COM1	Retail Trade	0.6	2.9	14.7	29.4
13	COM2	Wholesale Trade	0.6	3.2	16.2	32.4
14	COM3	Personal and Repair Services	0.3	1.6	8.1	16.2
15	COM4	Professional/Technical/Business Services	0.4	1.9	9.6	19.2
16	COM5	Banks/Financial Institutions	0.3	1.4	6.9	13.8
17	COM6	Hospital	0.2	1.4	7.0	14.0
18	COM7	Medical Office/Clinic	0.3	1.4	7.2	14.4
19	COM8	Entertainment & Recreation	0.2	1.0	5.0	10.0
20	COM9	Theaters	0.3	1.2	6.1	12.2
21	COM10	Parking	1.3	6.1	30.4	60.9
22	IND1	Heavy Industrial	0.4	1.6	7.8	15.7
23	IND2	Light Industrial	0.4	1.6	7.8	15.7
24	IND3	Food/Drugs/Chemicals	0.4	1.6	7.8	15.7
25	IND4	Metals/Minerals Processing	0.4	1.6	7.8	15.7
26	IND5	High Technology	0.4	1.6	7.8	15.7
27	IND6	Construction	0.4	1.6	7.8	15.7
28	AGR1	Agriculture	0.8	4.6	23.1	46.2
29	REL1	Church/Membership Organization	0.3	2.0	9.9	19.8
30	GOV1	General Services	0.3	1.8	9.0	17.9
31	GOV2	Emergency Response	0.3	1.5	7.7	15.3
32	EDU1	Schools/Libraries	0.4	1.9	9.5	18.9
33	EDU2	Colleges/Universities	0.2	1.1	5.5	11.0

Note that damage state "None" does not contribute to the calculation of the cost of structural damage and thus the summation in Equation 11-2 is from damage state “Slight” to “Complete”.

A similar calculation is performed for nonstructural damage. Nonstructural damage is broken down into acceleration-sensitive damage (damage to ceilings, equipment that is an integral part of the facility, such as mechanical and electrical equipment, piping, and elevators) and drift-sensitive damage (partitions, exterior walls, ornamentation, and glass). Nonstructural damage does not include the damage to contents such as furniture and computers that is accounted for in Section 11.2.2.

Nonstructural damage costs are calculated as follows:

Equation 11-3

$$\mathrm{CNSA}_{\mathrm{ds,i}} = \mathrm{BRC}_{\mathrm{i}} * \mathrm{PONSA}_{\mathrm{ds,i}} * \mathrm{RCA}_{\mathrm{ds,i}}$$

Equation 11-4

$$\mathrm{CNSA}_{\mathrm{i}} = \sum_{\mathrm{ds}=2}^{5} \mathrm{CNSA}_{\mathrm{ds,i}}$$

Equation 11-5

$$\mathrm{CNSD}_{\mathrm{ds,i}} = \mathrm{BRC}_{\mathrm{i}} * \mathrm{PONSD}_{\mathrm{ds,i}} * \mathrm{RCD}_{\mathrm{ds,i}}$$

Equation 11-6

$$\mathrm{CNSD}_{\mathrm{i}} = \sum_{\mathrm{ds}=2}^{5} \mathrm{CNSD}_{\mathrm{ds,i}}$$

Where:

$CNSA_{ds,I}$	is the cost of acceleration-sensitive nonstructural damage (repair costs) for damage state ds, and occupancy class, i
$CNSA_{i}$	is the cost of acceleration-sensitive nonstructural damage (repair costs) for occupancy class, i
$CNSD_{ds,i}$	is the cost of drift-sensitive nonstructural damage (repair costs) for damage state ds, and occupancy class, i
$CNSD_{i}$	is the cost of drift-sensitive nonstructural damage (repair costs) for occupancy class, i
BRC_{i}	is the building replacement cost of the occupancy class, i, as described in the *Hazus Inventory Technical Manual*
$PONSA_{ds,i}$	is the probability of the occupancy, I, being in nonstructural acceleration-sensitive damage state, ds (see Section 5)
$PONSD_{ds,i}$	is the probability of the occupancy class, i, being in nonstructural drift-sensitive damage state, ds (see Section 5)
$RCA_{ds,I}$	is the acceleration-sensitive nonstructural repair cost ratio (in % of building replacement cost) for occupancy class, I, in damage state, ds (Table 11 3)
$RCD_{ds,I}$	is the drift-sensitive nonstructural repair cost ratio (in % of building replacement cost) for the occupancy class, I, in damage state ds (Table 11 4)

Table 11-3 and Table 11-4 show the baseline values for the repair cost ratios of the acceleration-sensitive and drift-sensitive nonstructural components, respectively. As noted above, acceleration sensitive nonstructural components include hung ceilings, mechanical and electrical equipment, and elevators. Drift sensitive components include partitions, exterior wall panels, and glazing. The relative percentages of drift and acceleration sensitive components are based on the replacement cost model component costs for each occupancy class (for more information, refer to the Hazus Inventory Technical Manual).

The damage ratios given in Table 11-2, Table 11-3, and Table 11-4 are expressed as a percentage of the building replacement value. These values are consistent with and in the range of the damage definitions and corresponding damage ratios presented in *ATC-13 Earthquake Damage Evaluation Data for California* (ATC, 1985).

To determine the total cost of nonstructural damage for occupancy class i (CNSi), Equation 11-4 and Equation 11-6 must be summed.

Equation 11-7

$$\mathrm{CNS_i = CNSA_i + CNSD_i}$$

The total cost of building damage ($\mathrm{CBD_i}$) for occupancy class (i) is the sum of the structural and nonstructural damage.

Equation 11-8

$$\mathrm{CBD_i = CS_i + CNS_i}$$

Finally, to determine the total cost of building damage (CBD) for all occupancy classes, Equation 11-8 must be summed over all occupancy classes.

Equation 11-9

$$\mathrm{CBD} = \sum_{\mathrm{i=1}}^{33} \mathrm{CBD_i}$$

Table 11-3 Acceleration-Sensitive Nonstructural Repair Cost Ratios (in % of building replacement cost)

No.	Label	Occupancy Class	Acceleration-Sensitive Nonstructural Damage State			
			Slight	Moderate	Extensive	Complete
1	RES1	Single-family Dwelling	0.5	2.7	8.0	26.6
2	RES2	Mobile Home	0.8	3.8	11.3	37.8
3 - 8	RES3A-F	Multi-family Dwelling	0.8	4.3	13.1	43.7
9	RES4	Temporary Lodging	0.9	4.3	13.0	43.2
10	RES5	Institutional Dormitory	0.8	4.1	12.4	41.2
11	RES6	Nursing Home	0.8	4.1	12.2	40.8
12	COM1	Retail Trade	0.8	4.4	12.9	43.1
13	COM2	Wholesale Trade	0.8	4.2	12.4	41.1
14	COM3	Personal and Repair Services	1.0	5.0	15.0	50.0
15	COM4	Professional/Technical/Business Services	0.9	4.8	14.4	47.9
16	COM5	Banks/Financial Institutions	1.0	5.2	15.5	51.7
17	COM6	Hospital	1.0	5.1	15.4	51.3
18	COM7	Medical Office/Clinic	1.0	5.2	15.3	51.2
19	COM8	Entertainment & Recreation	1.1	5.4	16.3	54.4
20	COM9	Theaters	1.0	5.3	15.8	52.7
21	COM10	Parking	0.3	2.2	6.5	21.7
22	IND1	Heavy Industrial	1.4	7.2	21.8	72.5
23	IND2	Light Industrial	1.4	7.2	21.8	72.5
24	IND3	Food/Drugs/Chemicals	1.4	7.2	21.8	72.5
25	IND4	Metals/Minerals Processing	1.4	7.2	21.8	72.5
26	IND5	High Technology	1.4	7.2	21.8	72.5
27	IND6	Construction	1.4	7.2	21.8	72.5
28	AGR1	Agriculture	0.8	4.6	13.8	46.1
29	REL1	Church/Membership Organization	0.9	4.7	14.3	47.6
30	GOV1	General Services	1.0	4.9	14.8	49.3
31	GOV2	Emergency Response	1.0	5.1	15.1	50.5
32	EDU1	Schools/Libraries	0.7	3.2	9.7	32.4
33	EDU2	Colleges/Universities	0.6	2.9	8.7	29.0

Table 11-4 Drift-Sensitive Nonstructural Repair Costs (in % of building replacement cost)

No.	Label	Occupancy Class	Drift-Sensitive Nonstructural Damage State			
			Slight	Moderate	Extensive	Complete
1	RES1	Single-family Dwelling	1.0	5.0	25.0	50.0
2	RES2	Mobile Home	0.8	3.8	18.9	37.8
3 – 8	RES3A-F	Multi-family Dwelling	0.9	4.3	21.3	42.5
9	RES4	Temporary Lodging	0.9	4.3	21.6	43.2
10	RES5	Institutional Dormitory	0.8	4.0	20.0	40.0
11	RES6	Nursing Home	0.8	4.1	20.4	40.8
12	COM1	Retail Trade	0.6	2.7	13.8	27.5
13	COM2	Wholesale Trade	0.6	2.6	13.2	26.5
14	COM3	Personal and Repair Services	0.7	3.4	16.9	33.8
15	COM4	Professional/Technical/Business Services	0.7	3.3	16.4	32.9
16	COM5	Banks/Financial Institutions	0.7	3.4	17.2	34.5
17	COM6	Hospital	0.8	3.5	17.4	34.7
18	COM7	Medical Office/Clinic	0.7	3.4	17.2	34.4
19	COM8	Entertainment & Recreation	0.7	3.6	17.8	35.6
20	COM9	Theaters	0.7	3.5	17.6	35.1
21	COM10	Parking	0.4	1.7	8.7	17.4
22	IND1	Heavy Industrial	0.2	1.2	5.9	11.8
23	IND2	Light Industrial	0.2	1.2	5.9	11.8
24	IND3	Food/Drugs/Chemicals	0.2	1.2	5.9	11.8
25	IND4	Metals/Minerals Processing	0.2	1.2	5.9	11.8
26	IND5	High Technology	0.2	1.2	5.9	11.8
27	IND6	Construction	0.2	1.2	5.9	11.8
28	AGR1	Agriculture	0.0	0.8	3.8	7.7
29	REL1	Church/Membership Organization	0.8	3.3	16.3	32.6
30	GOV1	General Services	0.7	3.3	16.4	32.8
31	GOV2	Emergency Response	0.7	3.4	17.1	34.2
32	EDU1	Schools/Libraries	0.9	4.9	24.3	48.7
33	EDU2	Colleges/Universities	1.2	6.0	30.0	60.0

Note that the values in the last column of Table 11-2, Table 11-3, and Table 11-4 (i.e., structural and nonstructural repair costs for the Complete damage state) must sum to 100 since the Complete damage state implies that the structure must be replaced. The replacement value of the building is the sum of the value of the structural and nonstructural components.

11.2.2 Building Contents Losses

Building contents are defined as furniture, equipment that is not integral to the structure, computers, and other supplies. Contents do not include business inventories or nonstructural components such as lighting, ceilings, mechanical and electrical equipment, and other fixtures. It is assumed that most contents damage, such as overturned cabinets and equipment, or equipment sliding off tables and counters, is a function of building acceleration. Therefore, acceleration-sensitive nonstructural damage is considered to be a good indicator of contents damage. That is, if there is no acceleration-sensitive nonstructural damage, it is unlikely that there will be contents damage.

The cost of contents damage is calculated as follows:

Equation 11-10

$$\mathrm{CCD_i} = \mathrm{CRV_i} * \sum_{\mathrm{ds}=2}^{5} \mathrm{CD_{ds,i}} * \mathrm{PONSA_{ds,i}}$$

Where:

$\mathrm{CCD_i}$	is the cost of contents damage for occupancy class, i
$\mathrm{CRV_i}$	is the contents replacement value for occupancy class, i, as described in the *Hazus Inventory Technical Manual*
$\mathrm{CD_{ds,i}}$	is the contents damage ratio for occupancy class, i, in damage state, ds (from Table 11-5)
$\mathrm{PONSA_{ds,i}}$	is the probability of occupancy class, i, being in acceleration-sensitive nonstructural damage state ds

The contents damage ratios in Table 11-5 assume that at the Complete damage state, some percentage of contents (set at 50% as a default), can be retrieved. At the present time, contents damage percentages in Table 11-5 are the same for all occupancies.

Table 11-5 Contents Damage Ratios (in % of contents replacement cost)

Occupancy Class	Acceleration Sensitive Nonstructural Damage State			
	Slight	Moderate	Extensive	Complete
All Occupancies	1	5	25	50

** At the "Complete" Damage State, it is assumed that some salvage of contents will take place.*

11.2.3 Business Inventory Losses

Business inventories vary considerably with occupancy. Occupancies assumed by Hazus to have business inventories on hand include retail and wholesale trade (COM1, COM2), all of the industrial occupancies (IND1-IND6), and agriculture (AGR1). For example, the value of inventory for a high-tech manufacturing facility would be very different from that of a retail store. It is assumed that business inventory for each occupancy class is based on annual sales. Similar to building contents, it is assumed that acceleration-sensitive nonstructural damage is a good indicator of losses to business inventory, since business inventory losses most likely occur from stacks of inventory falling over, objects falling off shelves, or from water damage when piping breaks. Business inventory losses are estimated as the product of the total inventory value of buildings of a given occupancy (floor area times the percent of gross sales or production per square foot) in a given acceleration-sensitive damage state, the percent loss to the inventory for the damage state and the probability of the damage state.

The business inventory losses are given by the following expressions:

Equation 11-11

$$\mathrm{INV_i} = \mathrm{FA_i} * \mathrm{SALES_i} * \mathrm{BI_i} * \sum_{\mathrm{ds}=2}^{5} \mathrm{PONSA_{ds,i}} * \mathrm{INVD_{ds,i}}$$

Equation 11-12

$$\mathrm{INV} = \mathrm{INV_7} + \mathrm{INV_8} + \sum_{\mathrm{i}=17}^{23} \mathrm{INV_i}$$

Where:

$\mathrm{INV_i}$	is the value of inventory losses for occupancy class, i, where i=7 (COM1), 8 (COM2), and 17 (IND1) through 23 (AGR1)
$\mathrm{FA_i}$	is the floor area of occupancy class, i (in square feet)
$\mathrm{SALES_i}$	is the annual gross sales or production (per square foot) for the occupancy class, i (see *Hazus Inventory Technical Manual* for additional discussion and tabulated values for the relevant occupancies)
$\mathrm{BI_i}$	is business inventory as a percentage of annual gross sales for the occupancy class, i (see the *Hazus Inventory Technical Manual* for additional discussion and tabulated values for the relevant occupancies)
$\mathrm{PONSA_{ds,i}}$	is the probability of the occupancy class, i, being in acceleration-sensitive nonstructural damage state, ds
$\mathrm{INVD_{ds,i}}$	is percent inventory damage for the occupancy class, i, in damage state, ds (from Table 11-6)
INV	is total value of inventory losses for all relevant occupancies

Table 11-6 Percent Business Inventory Damage

No.	Label	Occupancy Class	Acceleration-Sensitive Nonstructural Damage State			
			Slight	Moderate	Extensive	Complete*
7	COM1	Retail Trade	1	5	25	50
8	COM2	Wholesale Trade	1	5	25	50
17	IND1	Heavy Industrial	1	5	25	50
18	IND2	Light Industrial	1	5	25	50
19	IND3	Food/Drugs/Chemicals	1	5	25	50
20	IND4	Metals/Minerals Processing	1	5	25	50
21	IND5	High Technology	1	5	25	50

No.	Label	Occupancy Class	Acceleration-Sensitive Nonstructural Damage State			
			Slight	Moderate	Extensive	Complete*
22	IND6	Construction	1	5	25	50
23	AGR1	Agriculture	1	5	25	50

** At the "Complete" Damage State, it is assumed that some salvage of inventory will take place.*

The business inventory damage ratios in Table 11-6 assume that at the Complete damage state, some percentage of inventories (set at 50% as a default), can be retrieved. At the present time, inventory damage percentages are the same for all relevant occupancies.

11.2.4 Building Repair Time/Loss of Function

The damage state descriptions in Section 5 provide a basis for establishing loss of function and repair time. A distinction should be made between loss of function and repair time. Here, loss of function is the time that a facility is not capable of conducting business. Generally, loss of function will be shorter than repair time because businesses will rent alternative space while repairs and construction are being completed. The time to repair a damaged building can be divided into two parts: construction and clean-up time, and time to obtain financing, permits, and complete design. For the lower damage states, the construction time will be close to the real repair time. At the higher damage levels, several additional tasks must be undertaken that typically increase the actual repair time. These tasks, which may vary considerably in scope and time between individual projects, include:

- Decision-making (related to business or institutional constraints, plans, financial status, etc.)
- Negotiation with FEMA (for public and non-profit), SBA, etc.
- Negotiation with insurance company, if insured
- Obtaining financing
- Contract negotiation with design firm(s)
- Detailed inspections and recommendations
- Preparation of contract documents
- Obtaining building and other permits
- Bidding/negotiating construction contract
- Start-up and occupancy activities after construction completion

Building clean-up and repair times are presented in Table 11-7. These times represent estimates of the median time for actual clean-up and repair, or construction. These estimates are extended in Table 11-8 to account for the delays described above, i.e., decision-making, financing, inspection etc., and represent estimates of the median time for full recovery of building function.

Table 11-7 Building Clean-up and Repair Time (in Days)

No.	Label	Occupancy Class	Structural Damage State				
			None	Slight	Moderate	Extensive	Complete
1	RES1	Single-family Dwelling	0	2	30	90	180
2	RES2	Mobile Home	0	2	10	30	60
3 – 8	RES3A-F	Multi-family Dwelling	0	5	30	120	240
9	RES4	Temporary Lodging	0	5	30	120	240
10	RES5	Institutional Dormitory	0	5	30	120	240
11	RES6	Nursing Home	0	5	30	120	240
12	COM1	Retail Trade	0	5	30	90	180
13	COM2	Wholesale Trade	0	5	30	90	180
14	COM3	Personal and Repair Services	0	5	30	90	180
15	COM4	Professional/Technical/ Business Services	0	5	30	120	240
16	COM5	Banks/Financial Institutions	0	5	30	90	180
17	COM6	Hospital	0	10	45	180	360
18	COM7	Medical Office/Clinic	0	10	45	180	240
19	COM8	Entertainment & Recreation	0	5	30	90	180
20	COM9	Theaters	0	5	30	120	240
21	COM10	Parking	0	2	20	80	160
22	IND1	Heavy Industrial	0	10	30	120	240
23	IND2	Light Industrial	0	10	30	120	240
24	IND3	Food/Drugs/Chemicals	0	10	30	120	240
25	IND4	Metals/Minerals Processing	0	10	30	120	240
26	IND5	High Technology	0	20	45	180	360
27	IND6	Construction	0	5	20	80	160
28	AGR1	Agriculture	0	2	10	30	60
29	REL1	Church/Membership Organization	0	10	30	120	240
30	GOV1	General Services	0	10	30	120	240
31	GOV2	Emergency Response	0	5	20	90	180
32	EDU1	Schools/Libraries	0	10	30	120	240
33	EDU2	Colleges/Universities	0	10	45	180	360

Table 11-8 Building Recovery Time (in Days)

No.	Label	Occupancy Class	Structural Damage State				
			None	Slight	Moderate	Extensive	Complete
1	RES1	Single-family Dwelling	0	5	120	360	720
2	RES2	Mobile Home	0	5	20	120	240
3 - 8	RES3A-F	Multi-family Dwelling	0	10	120	480	960
9	RES4	Temporary Lodging	0	10	90	360	480
10	RES5	Institutional Dormitory	0	10	90	360	480
11	RES6	Nursing Home	0	10	120	480	960
12	COM1	Retail Trade	0	10	90	270	360
13	COM2	Wholesale Trade	0	10	90	270	360
14	COM3	Personal and Repair Services	0	10	90	270	360
15	COM4	Professional/Technical/ Business Services	0	20	90	360	480
16	COM5	Banks/Financial Institutions	0	20	90	180	360
17	COM6	Hospital	0	20	135	540	720
18	COM7	Medical Office/Clinic	0	20	135	270	540
19	COM8	Entertainment & Recreation	0	20	90	180	360
20	COM9	Theaters	0	20	90	180	360
21	COM10	Parking	0	5	60	180	360
22	IND1	Heavy Industrial	0	10	90	240	360
23	IND2	Light Industrial	0	10	90	240	360
24	IND3	Food/Drugs/Chemicals	0	10	90	240	360
25	IND4	Metals/Minerals Processing	0	10	90	240	360
26	IND5	High Technology	0	20	135	360	540
27	IND6	Construction	0	10	60	160	320
28	AGR1	Agriculture	0	2	20	60	120
29	REL1	Church/Membership Organization	0	5	120	480	960
30	GOV1	General Services	0	10	90	360	480
31	GOV2	Emergency Response	0	10	60	270	360
32	EDU1	Schools/Libraries	0	10	90	360	480
33	EDU2	Colleges/Universities	0	10	120	480	960

Repair times differ for the same damage state depending on building occupancy; simpler and smaller buildings will take less time to repair than more complex, heavily serviced, or larger buildings. It has also been noted that large, well-financed corporations can sometimes accelerate the repair time compared to normal construction procedures.

Establishment of a more realistic repair time does not translate directly into business or service interruption. For some businesses, actual building repair time is largely irrelevant, because these businesses can rent alternative space or use spare industrial/commercial capacity elsewhere. These factors are reflected in the building and service interruption time modifiers in Table 11-9, which are applied to the recovery time values in Table 11-8 to arrive at estimates of business interruption time for economic purposes. The factors in Table 11-7, Table 11-8, and Table 11-9 have been derived based on professional experience, using ATC-13 (ATC, 1985) as a starting point.

Table 11-9 Building and Service Interruption Time Multipliers

No.	Label	Occupancy Class	Structural Damage State				
			None	Slight	Moderate	Extensive	Complete
1	RES1	Single-family Dwelling	0	0	0.5	1.0	1.0
2	RES2	Mobile Home	0	0	0.5	1.0	1.0
3 – 8	RES3A-F	Multi-family Dwelling	0	0	0.5	1.0	1.0
9	RES4	Temporary Lodging	0	0	0.5	1.0	1.0
10	RES5	Institutional Dormitory	0	0	0.5	1.0	1.0
11	RES6	Nursing Home	0	0	0.5	1.0	1.0
12	COM1	Retail Trade	0.5	0.1	0.1	0.3	0.4
13	COM2	Wholesale Trade	0.5	0.1	0.2	0.3	0.4
14	COM3	Personal and Repair Services	0.5	0.1	0.2	0.3	0.4
15	COM4	Professional/Technical/ Business Services	0.5	0.1	0.1	0.2	0.3
16	COM5	Banks/Financial Institutions	0.5	0.1	0.05	0.03	0.03
17	COM6	Hospital	0.5	0.1	0.5	0.5	0.5
18	COM7	Medical Office/Clinic	0.5	0.1	0.5	0.5	0.5
19	COM8	Entertainment & Recreation	0.5	0.1	1.0	1.0	1.0
20	COM9	Theaters	0.5	0.1	1.0	1.0	1.0
21	COM10	Parking	0.1	0.1	1.0	1.0	1.0
22	IND1	Heavy Industrial	0.5	0.5	1.0	1.0	1.0
23	IND2	Light Industrial	0.5	0.1	0.2	0.3	0.4
24	IND3	Food/Drugs/Chemicals	0.5	0.2	0.2	0.3	0.4
25	IND4	Metals/Minerals Processing	0.5	0.2	0.2	0.3	0.4
26	IND5	High Technology	0.5	0.2	0.2	0.3	0.4
27	IND6	Construction	0.5	0.1	0.2	0.3	0.4
28	AGR1	Agriculture	0	0	0.05	0.1	0.2
29	REL1	Church/Membership Organization	1.0	0.2	0.05	0.03	0.03
30	GOV1	General Services	0.5	0.1	0.02	0.03	0.03
31	GOV2	Emergency Response	0.5	0.1	0.02	0.03	0.03
32	EDU1	Schools/Libraries	0.5	0.1	0.02	0.05	0.05
33	EDU2	Colleges/Universities	0.5	0.1	0.02	0.03	0.03

The business interruption times resulting from the application of the Table 11-9 multipliers to the recovery times shown in Table 11-8 represent median values for the probability of business or service interruption. For buildings in the None and Slight damage states, the time loss is assumed to be short, with cleanup by staff, but work can resume while repairs are being done. For most commercial and industrial businesses that suffer Moderate or Extensive damage, the business interruption time is shown as short, on the assumption that these concerns will find alternate ways of continuing their activities. The values in Table 11-9 also reflect the fact that some businesses will suffer longer outages or even fail completely. Church and Membership Organizations generally quickly find temporary accommodation, and government offices also resume operating almost immediately. It is also assumed that hospitals and medical offices can continue operating, perhaps with some temporary rearrangement and departmental relocation if necessary, after suffering Moderate or even greater damage.

For other businesses and facilities, the interruption time is assumed to be equal to, or approaching, the total time for repair. This applies to residential, entertainment, theaters, and parking facilities, whose revenue or continued service is dependent on the existence and continued operation of the facility.

The construction time modifiers from Table 11-9 are multiplied by the extended building recovery times in Table 11-8 to arrive at loss of function time, as follows:

Equation 11-13

$$\mathrm{LOF_{ds}} = \mathrm{BRT_{ds}} * \mathrm{MOD_{ds}}$$

Where:

LOF_{ds}	is the loss of function time for damage state, ds
BRT_{ds}	is the building recovery time for damage state, ds (see Table 11-8)
MOD_{ds}	is the construction time modifiers for damage state, ds (See Table 11-9)

The loss of function time estimates are assumed to be median values, to be applied to a large inventory of facilities. At Moderate damage, some marginal businesses may close, while others will open after a day's cleanup. Even with Extensive damage, some businesses will accelerate repair, while a number will also close or be demolished. For example, a business operating in a URM building that suffers Moderate damage is more likely to be suffer business interruption than a business operating in a newer building that suffers Moderate, or even Extensive damage. If the URM building is a historic structure, its likelihood of survival and repair will probably increase. There will also be a small number of extreme cases: the slightly damaged building that becomes derelict, or the extensively damaged building that continues to function for years, with temporary shoring, until an expensive repair is financed and executed.

11.2.5 Relocation Expenses

Relocation costs may be incurred when the level of building damage is such that the building or portions of the building are unusable while repairs are being made. While relocation costs may include several expenses, this module only considers disruption costs that include the cost of shifting and transferring operations, and the rental of temporary space. It should be noted that the burden of relocation expenses is not expected to be borne by the renter. Instead, it is assumed that the building owners will incur the expense of moving their tenants to a new location. It should also be noted that a renter who has been displaced from a property due to earthquake damage would cease to pay rent to the owner of the damaged property and only pay rent to the new landlord. Therefore, the renter has no new rental expenses. If the damaged property is owner occupied, then the owner will have to pay for disruption costs in addition to the cost of rent for an alternate facility while the building is being repaired.

This module assumes that it is unlikely that an occupant will relocate if a building is in the None or Slight damage states, with the exception of some government or emergency response services that need to be operational immediately after an earthquake. These are considered to contribute very little to the total relocation expenses for a region and are ignored. It is assumed that entertainment (COM8), theaters (COM9), parking facilities (COM10), and heavy industry (IND1) will not relocate to new facilities. Instead they will resume operation when their facilities have been repaired or replaced.

Relocation expenses are estimated as a function of the type of occupancy, floor area, the rental costs per day per square foot for the occupancy type, a fixed disruption cost, the expected days of loss of function for each damage state, and the building’s structural damage state.

These are given by the following expression:

Equation 11-14

$$\mathrm{REL_i} = \mathrm{FA_i} * \left[(1 - \%00_\mathrm{i}) * \sum_{\mathrm{ds}=3}^{5} \left(\mathrm{POSTR_{ds,i}} * \mathrm{DC_i}\right) + \%00_\mathrm{i} * \sum_{\mathrm{ds}=3}^{5} \left(\mathrm{POSTR_{ds,i}} * (\mathrm{DC_i} + \mathrm{RENT_i} * \mathrm{RT_{ds}})\right)\right]$$

Where:

REL_i	is the relocation costs for the occupancy class, i, where i=1 (COM1) through 18 (COM7) and 23 (IND2) through 33 (EDU2)
FA_i	is the floor area of the occupancy class, i (in square feet)
$\%OO_i$	is percent owner occupied for the occupancy class, i (see the *Hazus Inventory Technical Manual* for a full description and tabulated values)
$POSTR_{ds,I}$	is the probability of the occupancy class, i, being in structural damage state, ds
DC_i	is the disruption costs for the occupancy class, i (dollars per square foot) (see the *Hazus Inventory Technical Manual* for a full description and tabulated values)
$RENT_i$	is the rental cost (dollars per square foot per day) for occupancy class, i (see the *Hazus Inventory Technical Manual* for a full description and tabulated values)
RT_{ds}	is the recovery time for damage state, ds (see Table 11-8)

11.2.6 Loss of Income

Business activity generates several types of income. First, there is income associated with capital, or property ownership. Business generates profits. A portion of profits is paid out to individuals (as well as to pension funds and other businesses) as dividends, while another portion (retained earnings) is invested back into the enterprise. Businesses also make interest payments to banks and bondholders for loans. They pay rent on property and make royalty payments for the use of tangible assets. Those in business for themselves, or in partnerships, generate a category called proprietary income, one portion of which reflects their profits and the other that reflects an imputed salary (e.g., the case of lawyers or dentists). Finally, the biggest category of income generated/paid is associated with labor. In most urban regions of the U.S., wage and salary income comprises more than 75% of total personal income payments.

It is possible to link income payments to various physical damage measures including sales, property values, or square footage. Income losses occur when building damage disrupts economic activity. Income losses are modeled as the product of floor area, income realized per square foot and the expected days of loss of function for each damage state.

Income losses are expressed as follows:

Equation 11-15

$$\mathrm{YLOS_i} = (1 - \mathrm{RF_i}) * \mathrm{FA_i} * \mathrm{INC_i} * \sum_{\mathrm{ds}=1}^{5} \mathrm{POSTR_{ds,i}} * \mathrm{LOF_{ds}}$$

Where:

$\mathrm{YLOS_i}$	is income losses for the occupancy class, i
$\mathrm{RF_i}$	is the recapture factor for the occupancy class, i (see *Hazus Inventory Technical Manual* for a full description and tabulated values)
$\mathrm{FA_i}$	is the floor area of the occupancy class, i (in square feet)
$\mathrm{INC_i}$	is income per day (per square foot) for the occupancy class, i (see the *Hazus Inventory Technical Manual* for a full description and tabulated values)
$\mathrm{POSTR_{ds}}$	is the probability of the occupancy class, i, being in structural damage state, ds (See Section 5)
$\mathrm{LOF_{ds}}$	is loss of function time for damage state, ds (See Section 11.2.4)

Recapture Factors

Business-related losses from earthquakes can be recouped, to some extent, by working overtime after the event. For example, a factory that is closed for six weeks due to structural damage or shortage of supplies may work extra shifts in the weeks or months following its reopening. Due to temporary closures of some facilities, there is likely to be a higher than normal demand. Undamaged firms will try to overcome input shortages, facilities that were temporarily closed will try to make-up their lost production, and firms outside the region will press for resumption of export sales to them.

This ability to “recapture” production will differ across industries. It will be higher for those that produce durable output and lower for those that produce perishables or “spot” products (examples of the latter being utility sales to residential customers, hotel services, and entertainment). Even some durable manufacturing enterprises would seem to have severe recapture limits because they already work three shifts per day. However, work on weekends, excess capacity, and temporary production facilities can be used to make up lost sales.

The *Hazus Inventory Technical Manual* provides a full set of recapture factors (wage, income, and output recapture factors) that can be used with Equation 11-15 to estimate the various types of income losses for the economic sectors used in the direct economic loss module.

11.2.7 Rental Income Losses

Rental income losses are the product of floor area, rental rates per square foot. and the expected recovery time for each damage state. Rental income losses include residential, commercial, and industrial properties. It is assumed that a renter will pay full rent if the property is in the None or Slight damage state. Thus, rental income losses are calculated only for the Moderate, Extensive, and Complete damage states. It should be noted that rental income is based upon the percentage of floor area in occupancy i that is being rented (which is equal to one minus the percent that is owner occupied).

Equation 11-16

$$\mathrm{RY_i} = (1 - \%\mathrm{OO_i}) * \mathrm{FA_i} * \mathrm{RENT_i} * \sum_{\mathrm{ds}=3}^{5} \mathrm{POSTR_{ds,i}} * \mathrm{RT_{ds}}$$

Where:

RY_i	is rental income losses for the occupancy class, i
$\%OO_i$	is percent owner occupied for the occupancy class, i (see the *Hazus Inventory Technical Manual* for a full description and tabulated values)
FA_i	is the floor area of the occupancy class, i (in square feet)
$RENT_i$	is the rental cost (dollars per square foot per day) for an occupancy class, i (see the *Hazus Inventory Technical Manual* for a full description and tabulated values)
$POSTR_{ds,i}$	is the probability of a occupancy class, i, being in structural damage state, ds (see Section 5)
RT_{ds}	is recovery time for damage dtate, ds (see Section 11.2.4)

11.3 Description of Methodology: Utility and Transportation Systems

This section describes the methodologies used to estimate transportation and utility system-related direct economic losses. Direct physical damage to transportation and utility systems was discussed in Section 7 and Section 8, respectively.

Direct economic losses are computed based on the following: (1) probabilities of being in a certain damage state ($P[D_s = ds_i]$), (2) the replacement value of the component, and (3) damage ratios (DR_i) for each damage state, ds_i. Replacement values for all utility and transportation system components are discussed in the *Hazus Inventory Technical Manual*. Economic losses are evaluated by multiplying the compounded damage ratio (DR_c) by the replacement value. The compounded damage ratio is computed as the probabilistic combination of damage ratios as follows:

Equation 11-17

$$\mathrm{DR_c} = \sum_{\mathrm{i}=2}^{5} \mathrm{DR_i} * \mathrm{P[ds_i]}$$

Where:

$P[ds_i]$	is the probability of being in damage state i, and 1, 2, 3, 4, and 5 are associated with damage states None, Slight, Moderate, Extensive, and Complete. No losses are associated with damage state 1 (None), therefore, the summation is from i=2 to 5.

Determining the probability of being in or exceeding a certain damage state ($P[D_S \geq d_{si} \mid PGA \text{ or } PGD]$), for each utility and transportation component was discussed in Section 7 and Section 8. From the damage state exceedance probabilities (probability of being in or exceeding a given damage state), discrete damage state occurrence probabilities (probabilities of being in a given damage state) may be derived, as shown in Equation 11-18 through Equation 11-22 for the None, Slight, Moderate, Extensive, and Complete damage states, respectively. Estimates of the replacement value of all utility and transportation system components are provided in the *Hazus Inventory Technical Manual*.

Equation 11-18

$$\mathbf{P_1} = \mathrm{P}[\mathrm{D_s} = \mathrm{ds_1} \mid \mathrm{PGA\ or\ PGD}] = 1 - \mathrm{P}[\mathrm{D_s} \geq \mathrm{ds_2} \mid \mathrm{PGA\ or\ PGD}]$$

Equation 11-19

$$\mathbf{P_2 =} [\mathrm{D_s} \mathbf{=} \mathrm{ds_2} \mid \mathrm{PGA\ or\ PGD}] \mathbf{=} \mathrm{P}[\mathrm{D_s} \geq \mathrm{ds_2} \mid \mathrm{PGA\ or\ PGD}] - \mathrm{P}[\mathrm{D_s} \geq \mathrm{ds_3} \mid \mathrm{PGA\ or\ PGD}]$$

Equation 11-20

$$\mathbf{P_3} = \mathrm{P}[\mathrm{D_s} = \mathrm{ds_3} \mid \mathrm{PGA\ or\ PGD}] = \mathrm{P}[\mathrm{D_s} \geq \mathrm{ds_3} \mid \mathrm{PGA\ or\ PGD}] - \mathrm{P}[\mathrm{D_s} \geq \mathrm{ds_4} \mid \mathrm{PGA\ or\ PGD}]$$

Equation 11-21

$$\mathbf{P_4} = \mathrm{P}[\mathrm{D_s} = \mathrm{ds_4} \mid \mathrm{PGA\ or\ PGD}] = \mathrm{P}[\mathrm{D_s} \geq \mathrm{ds_4} \mid \mathrm{PGA\ or\ PGD}] - \mathrm{P}[\mathrm{D_s} \geq \mathrm{ds_5} \mid \mathrm{PGA\ or\ PGD}]$$

Equation 11-22

$$\mathbf{P_5} = \mathrm{P}[\mathrm{D_s} = \mathrm{ds_5} \mid \mathrm{PGA\ or\ PGD}] = \mathrm{P}[\mathrm{D_s} \geq \mathrm{ds_5} \mid \mathrm{PGA\ or\ PGD}]$$

11.3.1 Transportation Systems

This section describes the methodologies used to estimate direct economic losses related to transportation system damage. Transportation systems include highway, railway, light rail, bus, port, ferry, and airport systems. Damage models for each of these systems were discussed in detail in Section 7.

11.3.1.1 Highway Systems

In this subsection, damage ratios are presented for each damage state for roadways, highway bridges, and highway tunnels. Damage ratios for roadways are expressed as a fraction of the roadway replacement cost per unit length. Damage ratios for bridges are expressed as a fraction of the bridge replacement cost. Damage ratios for highway tunnels are expressed as a fraction of the liner replacement cost per unit length. The damage ratios for roadways, tunnels, and bridges are presented in Table 11-10.

Table 11-10 Damage Ratios for Highway System Components

Classification	Damage State	Best Estimate Damage Ratio	Range of Damage Ratios
Roadways	Slight	0.05	0.01 to 0.15
	Moderate	0.20	0.15 to 0.40
	Extensive/Complete	0.70	0.40 to 1.00
Tunnel's Lining	Slight	0.01	0.01 to 0.15
	Moderate	0.30	0.15 to 0.40
	Extensive	0.70	0.40 to 0.80
	Complete	1.00	0.80 to 1.00
Bridges	Slight	0.03	0.01 to 0.03
	Moderate	0.08	0.02 to 0.15
	Extensive	0.25	0.10 to 0.40
	Complete	1.00*	0.30 to 1.00

** If the number of spans is greater than two, then the best estimate damage ratio for Complete damage is [2/(number of spans)]*

11.3.1.2 Railway Systems

In this subsection, damage ratios are presented for each damage state for railway tracks/roadbeds, railway bridges, railway tunnels, and for the various types of railway facilities. Damage ratios for tracks are expressed as a fraction of the replacement cost per length. Damage ratios associated with bridges and facilities are expressed as a fraction of the component replacement cost. Damage ratios for railway tunnels are expressed as a fraction of the liner replacement cost per unit length.

The damage ratios for railway bridges, fuel facilities, dispatch facilities, urban stations, and maintenance facilities are presented in Table 11-11. The damage ratios for railway tracks and tunnels are the same as for urban roads and tunnels for the highway systems presented in Section 11.3.1.1. The damage ratios for fuel and dispatch facilities were derived from damage ratios of the facility subcomponents multiplied by their respective percentages of the total component (fuel or dispatch facility) value. Further information on the subcomponent damage ratios and values can be found in Appendix A.

Table 11-11 Damage Ratios for Railway System Components

Classification	Damage State	Best Estimate Damage Ratio	Range of Damage Ratios
Bridges	Slight	0.03	0.01 to 0.03
	Moderate	0.08	0.02 to 0.15
	Extensive	0.25	0.10 to 0.40
	Complete	1.00	0.30 to 1.00
Fuel Facilities	Slight	0.15	0.01 to 0.15
	Moderate	0.40	0.15 to 0.40
	Extensive	0.80	0.40 to 0.80
	Complete	1.00	0.80 to 1.00

Classification	Damage State	Best Estimate Damage Ratio	Range of Damage Ratios
Dispatch Facilities	Slight	0.10	0.01 to 0.15
	Moderate	0.40	0.15 to 0.40
	Extensive	0.80	0.40 to 0.80
	Complete	1.00	0.80 to 1.00
Urban Stations and Maintenance Facilities	Slight	0.10	0.01 to 0.15
	Moderate	0.40	0.15 to 0.40
	Extensive	0.80	0.40 to 0.80
	Complete	1.00	0.80 to 1.00

11.3.1.3 Light Rail Systems

In this subsection, damage ratios are presented for each damage state for light rail tracks/roadbeds, bridges, tunnels, and facilities. Damage ratios for bridges and facilities are expressed as a fraction of the component replacement cost. Damage ratios for tracks are expressed as a fraction of the replacement value per unit length. Damage ratios for light rail tunnels are expressed as a fraction of the linear replacement cost per unit length.

The damage ratios for light rail tracks, bridges, and tunnels are the same as for urban roads, bridges, and tunnels for highway systems presented in Section 11.3.1.1. The damage ratios for dispatch and maintenance facilities are the same as those for railway systems presented in Section 11.3.1.2. The damage ratios for DC substations are presented in Table 11-12. The damage ratios for DC substations were derived from damage ratios of the facility subcomponents multiplied by their respective percentages of the total facility value. Further information on the subcomponent damage ratios and values can be found in Appendix A.

Table 11-12 Damage Ratios for DC Substations

Classification	Damage State	Best Estimate Damage Ratio	Range of Damage Ratios
DC Substations	Slight	0.10	0.01 to 0.15
	Moderate	0.40	0.15 to 0.40
	Extensive	0.80	0.40 to 0.80
	Complete	1.00	0.80 to 1.00

11.3.1.4 Bus Systems

In this subsection, damage ratios are presented for each damage state for urban bus stations and bus maintenance, fuel, and dispatch facilities. Damage ratios for these components are expressed as a fraction of the component replacement cost.

The damage ratios for urban stations, maintenance facilities, fuel facilities, and dispatch facilities are the same as those for railway systems presented in Section 11.3.1.2.

11.3.1.5 Port Systems

In this subsection, damage ratios are presented for each damage state for waterfront structures (e.g., wharves, piers, and seawalls), cranes and cargo handling equipment, fuel facilities, and warehouses. Damage ratios for these components are expressed as a fraction of the component replacement cost. The damage ratios for port system components are presented in

Table 11-13. The damage ratios for fuel facilities are the same as those for railway systems presented in Section 11.3.1.2.

Table 11-13 Damage Ratios for Port System Components

Classification	Damage State	Best Estimate Damage Ratio	Range of Damage Ratios
Waterfront Structures	Slight	0.10	0.01 to 0.15
	Moderate	0.40	0.15 to 0.40
	Extensive	0.80	0.40 to 0.80
	Complete	1.00	0.80 to 1.00
Cranes/Cargo Handling Equipment	Slight	0.05	0.01 to 0.15
	Moderate	0.25	0.15 to 0.40
	Extensive/Complete	0.75	0.40 to 1.00
Warehouses	Slight	0.10	0.01 to 0.15
	Moderate	0.40	0.15 to 0.40
	Extensive	0.80	0.40 to 0.80
	Complete	1.00	0.80 to 1.00

11.3.1.6 Ferry Systems

In this subsection, damage ratios are presented for each damage state for ferry waterfront structures (e.g., wharves, piers, and seawalls), fuel, maintenance, and dispatch facilities, and passenger terminals. Damage ratios for ferry system components are expressed as a fraction of the component replacement cost.

The damage ratios for waterfront structures are the same as those for port systems given in Section 11.3.1.5. The damage ratios for fuel, maintenance and dispatch facilities are the same as those for railway systems presented in Section 11.3.1.2. The damage ratios for passenger terminals are the same as those for urban stations in railway systems.

11.3.1.7 Airport Systems

In this subsection, damage ratios are presented for each damage state for airport runways, control towers, fuel facilities, terminal buildings, maintenance and hangar facilities, and parking structures. Damage ratios for the airport system components are expressed as a fraction of the component replacement cost.

The damage ratios for airport system components are presented in Table 11-14. The damage ratios for fuel facilities and maintenance facilities are the same as those for railway systems presented in Section 11.3.1.2, and damage ratios for terminal buildings are the same as those used for urban stations in railway systems.

Table 11-14 Damage Ratios for Airport System Components

Classification	Damage State	Best Estimate Damage Ratio	Range of Damage Ratios
Runways	Slight	0.10	0.01 to 0.15
	Moderate	0.40	0.15 to 0.40
	Extensive	0.80	0.40 to 0.80
	Complete	1.00	0.80 to 1.00
Control Towers	Slight	0.10	0.01 to 0.15
	Moderate	0.40	0.15 to 0.40
	Extensive	0.80	0.40 to 0.80
	Complete	1.00	0.80 to 1.00
Parking Structures	Slight	0.10	0.01 to 0.15
	Moderate	0.40	0.15 to 0.40
	Extensive	0.80	0.40 to 0.80
	Complete	1.00	0.80 to 1.00

11.3.2 Utility Systems

This section describes the methodologies used to estimate direct economic losses related to utility system damage. Utility systems include potable water, wastewater, oil, natural gas, electric power, and communication systems. The estimation of the direct economic losses associated with each of these systems is presented in the following sections.

11.3.2.1 Potable Water Systems

In this subsection, damage ratios are presented for each damage state for water treatment plants, wells, storage tanks, and pumping plants. The damage ratios for these facilities were derived from damage ratios of the facility subcomponents multiplied by their respective percentages of the total facility value. Further information on the subcomponent damage ratios and values can be found in Appendix B. Damage ratios are presented in Table 11-15. For potable water system pipelines, repair costs are provided directly for leaks and breaks, and are documented in the *Hazus Inventory Technical Manual*.

Table 11-15 Damage Ratios for Potable Water System Components

Classification	Damage State	Best Estimate Damage Ratio	Range of Damage Ratios
Water Treatment Plants	Slight	0.08	0.01 to 0.15
	Moderate	0.40	0.15 to 0.40
	Extensive	0.77	0.40 to 0.80
	Complete	1.00	0.80 to 1.00
Storage Tanks	Slight	0.20	0.01 to 0.15
	Moderate	0.40	0.15 to 0.40
	Extensive	0.80	0.40 to 0.80
	Complete	1.00	0.80 to 1.00

Classification	Damage State	Best Estimate Damage Ratio	Range of Damage Ratios
Wells and Pumping Plants	Slight	0.05	0.01 to 0.15
	Moderate	0.38	0.15 to 0.40
	Extensive	0.80	0.40 to 0.80
	Complete	1.00	0.80 to 1.00

11.3.2.2 Wastewater Systems

In this subsection, damage ratios are presented for each damage state for underground sewers and interceptors, wastewater treatment plants, and lift stations. Damage ratios for these components are expressed as a fraction of the component replacement cost (for wastewater treatment plants and lift stations), or as repair costs for sewers and interceptors.

The damage ratios for lift stations are same as those for pumping plants in potable water systems presented in Section 11.3.2.1. The damage ratios for wastewater treatment plants, presented in Table 11-16, were derived from damage ratios of the facility subcomponents multiplied by their respective percentages of the total facility value. Further information on the subcomponent damage ratios and values can be found in Appendix B. For sewers and interceptors, repair costs are provided directly for leaks and breaks, and are documented in the *Hazus Inventory Technical Manual*.

Table 11-16 Damage Ratios for Wastewater System Components

Classification	Damage State	Best Estimate Damage Ratio	Range of Damage Ratios
Wastewater Treatment Plants	Slight	0.10	0.01 to 0.15
	Moderate	0.37	0.15 to 0.40
	Extensive	0.65	0.40 to 0.80
	Complete	1.00	0.80 to 1.00

11.3.2.3 Oil Systems

In this subsection, damage ratios are presented for each damage state for refineries, pumping plants, and tank farms. Damage ratios for these components were derived from damage ratios of the facility subcomponents multiplied by their respective percentages of the total facility value. Further information on the subcomponent damage ratios and values can be found in Appendix B. The damage ratios for oil system components are presented in Table 11-17.

For buried oil pipelines, repair costs are provided directly for leaks and breaks, and are documented in the *Hazus Inventory Technical Manual*.

Table 11-17 Damage Ratios for Oil System Components

Classification	Damage State	Best Estimate Damage Ratio	Range of Damage Ratios
Refineries	Slight	0.09	0.01 to 0.15
	Moderate	0.23	0.15 to 0.40
	Extensive	0.78	0.40 to 0.80
	Complete	1.00	0.80 to 1.00

Classification	Damage State	Best Estimate Damage Ratio	Range of Damage Ratios
Pumping Plants	Slight	0.08	0.01 to 0.15
	Moderate	0.40	0.15 to 0.40
	Extensive	0.80	0.40 to 0.80
	Complete	1.00	0.80 to 1.00
Tank Farms	Slight	0.13	0.01 to 0.15
	Moderate	0.40	0.15 to 0.40
	Extensive	0.80	0.40 to 0.80
	Complete	1.00	0.80 to 1.00

11.3.2.4 Natural Gas Systems

In this subsection, damage ratios are presented for each damage state for buried pipes and compressor stations. The damage ratios for compressor stations are the same as those for pumping plants in oil systems shown in Table 11-17. Damage ratios for these components are expressed as a fraction of the component replacement cost. For buried natural gas pipelines, repair costs are provided directly for leaks and breaks, and are documented in the *Hazus Inventory Technical Manual*.

11.3.2.5 Electric Power Systems

In this subsection, damage ratios are presented for each damage state for substations, distribution circuits, and generation plants. Damage ratios for these components were derived from damage ratios of the facility subcomponents multiplied by their respective percentages of the total facility value. Further information on the subcomponent damage ratios and values can be found in Appendix B. The damage ratios for electric power system components are presented in Table 11-18.

Table 11-18 Damage Ratios for Electric Power System Components

Classification	Damage State	Best Estimate Damage Ratio	Range of Damage Ratios
Substations	Slight	0.05	0.01 to 0.15
	Moderate	0.11	0.15 to 0.40
	Extensive	0.55	0.40 to 0.80
	Complete	1.00	0.80 to 1.00
Distribution Circuits	Slight	0.05	0.01 to 0.15
	Moderate	0.15	0.15 to 0.40
	Extensive	0.60	0.40 to 0.80
	Complete	1.00	0.80 to 1.00
Generation Plants	Slight	0.08	0.01 to 0.15
	Moderate	0.35	0.15 to 0.40
	Extensive	0.72	0.40 to 0.80
	Complete	1.00	0.80 to 1.00

11.3.2.6 Communication Systems

In this subsection, damage ratios are presented for each damage state for communication system central offices/broadcasting stations. Damage ratios for central offices were derived from damage ratios of the facility subcomponents multiplied by their respective percentages of the total facility value. Further information on the subcomponent damage ratios and values can be found in Appendix B: Subcomponent Damage Functions for Utility Systems. The damage ratios for central offices are presented in Table 11-19.

Table 11-19 Damage Ratios for Communication System Components

Classification	Damage State	Best Estimate Damage Ratio	Range of Damage Ratios
Central Office / Broadcasting Station	Slight	0.09	0.01 to 0.15
	Moderate	0.35	0.15 to 0.40
	Extensive	0.73	0.40 to 0.80
	Complete	1.00	0.80 to 1.00

Section 12. Direct Social Losses – Casualties

This section develops the methodology for the estimation of casualties, describes the format of outputs, and defines the required inputs. The methodology assumes there is a strong correlation between building damage (both structural and nonstructural) and the number and severity of casualties. In smaller earthquakes, nonstructural damage will most likely control the casualty estimates. In severe earthquakes, where there can be a large quantity of collapses and partial collapses, a proportionally larger number of fatalities will occur. There is a lack of quality data regarding earthquake related injuries. Datasets are not available for all specific building types. Available data often have insufficient information regarding the type of structure in which the casualties occurred, and the mechanism used to estimate potential casualties. An attempt to develop sophisticated models based on such data is neither feasible nor reliable.

12.1 Scope

This module provides a methodology for estimating casualties caused only by building and bridge damage. The module estimates casualties directly caused by structural or nonstructural damage, although nonstructural casualties are not directly derived from nonstructural damage but instead are derived from estimated structural damage. The method excludes casualties caused by heart attacks, car accidents, falls, power failure which causes failure of a respirator, incidents during post-earthquake search and rescue, post-earthquake clean-up and construction activities, electrocution, tsunami, dam failures, fires, hazardous materials releases, or landslides, liquefaction, and fault rupture, except those resulting in damage to buildings. Psychological impacts of the earthquake on the exposed population are not modeled. A study by Aroni and Durkin (1985) suggests that falls would add to the injury estimate. Studies by Durkin (1992, 1995) suggest that falls, heart attacks, car accidents, fire, and other causes not directly attributable to structural or nonstructural damage would increase the estimate of deaths.

Although fires following earthquakes have been the cause of significant casualties (notably in the firestorm following the 1923 Kanto, Japan, earthquake), such cases have involved the combination of a number of conditions, which have a low probability of occurrence in U.S. earthquakes. A more typical example of fires in the U.S is the catastrophic Oakland Hills fire of 1990, in which over 3,500 residences were destroyed, yet casualties were low. Similarly, there is the possibility (but low probability) of a large number of casualties due to tsunami, landslides, sudden failure of a critical dam, or a massive release of toxic substances. If the particular characteristics of the Study Region give the user cause for concern about the possibility of casualties from fire, tsunami, landslides, dam failure, or hazardous materials, it would be advisable to initiate specific studies directed towards the problem.

The scope of this module is to provide a simple and consistent framework for earthquake casualty estimation. Recognized relevant issues in casualty estimation such as occupancy potential, collapse and non-collapse vulnerability of the building stock, time of the earthquake occurrence, and spatial distribution of the damage, are included in the methodology. The methodology reflects:

- United States-specific casualty data, when available
- Interpretation of worldwide casualty data for casualty estimations in the United States
- Multidisciplinary inputs from engineering, medical, social science, and other disciplines involved with earthquake-related casualty estimation.

Data formats are flexible enough to handle currently available data, to re-evaluate previously collected data, and to accept new data as they become available.

12.1.1 Form of Casualty Estimate

The output from the casualty module consists of a breakdown of estimated casualties by injury severity level, defined by a four-level injury severity scale (Durkin and Thiel, 1991; Coburn and Spence, 1992; Cheu, 1994). Casualties are calculated at the Census tract level. The output is at the Census tract level and aggregated for the Study Region. Table 12-1 defines the injury classification scale used in the methodology.

Table 12-1 Injury Classification Scale

Injury Severity Level	Injury Description
Severity 1	Injuries requiring basic medical aid that could be administered by paraprofessionals. These types of injuries would require bandages or observation. Some examples are a sprain, a severe cut requiring stitches, a minor burn (first-degree or second-degree on a small part of the body), or a bump on the head without loss of consciousness. Injuries of lesser severity that could be self treated are not estimated by Hazus.
Severity 2	Injuries requiring a greater degree of medical care and use of medical technology such as x-rays or surgery, but not expected to progress to a life-threatening status. Some examples are third-degree burns or second-degree burns over large parts of the body, a bump on the head that causes loss of consciousness, or fractured bone.
Severity 3	Injuries that pose an immediate life-threatening condition if not treated adequately and expeditiously. Some examples are uncontrolled bleeding, punctured organ, other internal injuries, spinal column injuries, or crush syndrome.
Severity 4	Instantaneously killed or mortally injured

Other, more elaborate casualty scales exist, based on quantifiable medical parameters such as medical injury severity scores, coded physiologic variables, and other factors. The selected four-level injury scale represents an achievable compromise between the demands of the medical community (in order to plan their response), and the ability of the engineering community to provide the required data. For example, medical professionals would like to have the classification in terms of "Injuries/Illnesses" to account for worsened medical conditions caused by an earthquake (e.g., heart attack). However, currently available casualty assessment methodologies do not allow for a finer resolution in the casualty scale definition.

12.1.2 Input Requirements

There are three types of data used by the casualty module:

- Scenario time definition
- Data supplied by other modules
- Data specific to the casualty module, i.e., population distribution data

12.1.2.1 Scenario Time Definition

The methodology provides information necessary to produce casualty estimates for three times of day. The following time options are provided:

- Earthquake striking at 2:00 a.m. (nighttime scenario)
- Earthquake striking at 2:00 p.m. (daytime scenario)
- Earthquake striking at 5:00 p.m. (commute time scenario)

These scenarios are expected to generate the highest casualties for the population at home, the population at work/school, and the population during rush hour, respectively.

12.1.2.2 Data Supplied by Other Modules

Other modules supply inventory (building stock distribution) data and damage state probabilities. These data are provided at the Census tract level, including:

- *General Occupancy to Specific Building Type Mapping* - the module uses the relationship between the general occupancy classes and the specific building type, which is calculated by combining the following relationships.
- *Specific Occupancy to Specific Building Type Relationship* (see the *Hazus Inventory Technical Manual* for additional information)
- *General Occupancy to Specific Occupancy Relationship* (see the *Hazus Inventory Technical Manual* for additional information)
- *Damage State Probabilities* - the casualty module uses the four structural damage states (Slight, Moderate, Extensive, and Complete) computed by the direct physical damage module as well as the subset of the Complete damage state representing building collapse. For each Census tract and each specific building type, the probabilities of the structure being in each of the four damage states are required. In addition, bridge casualties are estimated using the probability of the Complete damage state for bridges.

12.1.2.3 Casualty Model Population Distribution Data

For use in the casualty module, the population in each Census tract is distributed into six groups associated with the various Hazus occupancy classes, and one group for commuters:

- Single-family Residential population (Hazus occupancy class RES1)
- Hotel population (RES4)
- Other Residential population (all other residential occupancies: RES2, RES3A-F, RES5 and RES6)
- Educational population (EDU1 and EDU2)
- Industrial population (IND1 – IND6)
- Commercial population (COM1 – COM10, AGR1, REL1, and GOV1-GOV2)
- Commuting population

The population distribution is calculated for the three times of day (nighttime, daytime, and commute time) from available demographic data for each Census tract (refer to the *Hazus*

Inventory Technical Manual for more information on the Hazus demographics data). Table 12-2 provides the relationships used to determine the population distributions employed by the casualty module. There are two multipliers associated with each entry in the table. The second multiplier indicates the fraction of a population component present in an occupancy for a particular scenario time. The first multiplier then divides that population component into indoors and outdoors. For example, at 2 a.m., the distribution assumes that 99% (0.99) of the nighttime residential population will be in a residential occupancy with 99.9% (0.999) of those people indoors, and 0.1% (0.001) outdoors. These factors could be changed, if better information is available. To change these factors, the user would need to edit the SQL table “eqAnalParams”; the parameters are not accessible through the Hazus GUI. For additional information, users may contact the Hazus Helpdesk.

The educational population calculation uses the factor of 0.80 multiplied by the number of children aged 16 and under; this reduction factor is intended to reflect the fact that children under the age of five are too young to attend to school and also represent the number of students not attending school due to illness or other factors. Average attendance figures for public and private schools should be used when modifying the educational occupancy values in Table 12-2. As noted above, to change these factors, the user would need to edit the SQL table “eqAnalParams” although these parameters are not accessible through the Hazus GUI. For additional information, users may contact the Hazus Helpdesk.

While Table 12-2 provides the population distribution factors for a single “Residential” occupancy class, the Hazus software calculates and reports casualties in single-family and other residential structures separately. For each Census tract, the ratio of single-family residential building (RES1) square footage to all “Residential” building square footage (i.e., all RES occupancy classes except hotels/RES4) is used to allocate the residential population accordingly.

Table 12-2 Default Relationships for Estimating Population Distributions

Distribution of People in Census Tract				
Occupancy		**2:00 a.m.**	**2:00 p.m.**	**5:00 p.m.**
Indoors	Residential	(0.999)0.99(NRES)	(0.70)0.75(DRES)	(0.70)0.5(NRES)
	Commercial	(0.999)0.02(COMW)	(0.99)0.98(COMW) + (0.80)0.20(DRES) + 0.80(HOTEL) + 0.80(VISIT)	0.98[0.50(COMW) + 0.10(NRES)+ 0.70(HOTEL)]
	Educational		(0.90)0.80(GRADE) + 0.80(COLLEGE)	(0.80)0.50(COLLEGE)
	Industrial	(0.999)0.10(INDW)	(0.90)0.80(INDW)	(0.90)0.50(INDW)
	Hotels	0.999(HOTEL)	0.19(HOTEL)	0.299(HOTEL)
Outdoors	Residential	(0.001)0.99(NRES)	(0.30)0.75(DRES)	(0.30)0.5(NRES)
	Commercial	(0.001)0.02(COMW)	(0.01)0.98(COMW) + (0.20)0.20(DRES) + (0.20)VISIT + 0.50(1-PRFIL)0.05(POP)	0.02[0.50(COMW) + 0.10(NRES) + 0.70(HOTEL)] + 0.50(1-PRFIL) [0.05(POP) + 1.0(COMM)]
	Educational		(0.10)0.80(GRADE) + 0.20(COLLEGE)	(0.20)0.50(COLLEGE)
	Industrial	(0.001)0.10(INDW)	(0.10)0.80(INDW)	(0.10)0.50(INDW)
	Hotels	0.001(HOTEL)	0.01(HOTEL)	0.001(HOTEL)

Distribution of People in Census Tract				
Occupancy		**2:00 a.m.**	**2:00 p.m.**	**5:00 p.m.**
Commute	Commuting in cars	0.005(POP)	(PRFIL)0.05(POP)	(PRFIL)[0.05(POP) + 1.0(COMM)]
	Commuting using other modes		0.50(1-PRFIL)0.05(POP)	0.50(1-PRFIL) [0.05(POP) + 1.0(COMM)]

Where:

POP	is the Census tract population taken from Census data (see the *Hazus Inventory Technical Manual* for additional information on the underlying Hazus demographics data).
DRES	is the daytime residential population inferred from Census data.
NRES	is the nighttime residential population inferred from Census data.
COMM	is the number of people commuting inferred from Census data.
COMW	is the number of people employed (working) in the commercial sector.
INDW	is the number of people employed (working) in the industrial sector.
GRADE	is the number of students in grade schools (K-12).
COLLEGE	is the number of students on college and university campuses in the Census tract.
HOTEL	is the number of people staying in hotels in the Census tract.
PRFIL	is a factor representing the proportion of commuters using automobiles, inferred from the profile of the community (0.60 for dense urban, 0.80 for less dense urban or suburban, and 0.85 for rural; the default value is 0.80).
VISIT	is the number of regional residents who do not live in the Study Area, visiting the Census tract for shopping and entertainment (the default value is set to 0.0).

The commuting population is defined as the number of people expected to be in vehicles, public transit, riding bicycles, and walking during commuting time. In this methodology, the only roadway casualties estimated are those incurred from bridge/overpass damage. This requires an estimate of the number of people that will be located on or under bridges during the earthquake. The methodology provides for a Commuter Distribution Factor, CDF, that corresponds to the percentage of the commuting population located on or under bridges; baseline values are CDF = 0.01 for daytime, CDF = 0.01 for nighttime and CDF = 0.02 during commute time. These values correspond to 10 or 20 persons per 1,000 commuters on or under a bridge for daytime and nighttime, respectively. The number of people on or under bridges in a Census tract is then computed as follows.

Equation 12-1

$$\mathrm{NBRDG} = \mathrm{CDF} * \mathrm{Commuter\ Population}$$

Where:

NBRDF	is the number of people on or under bridges in the Census tract.

CDF	is the Commuter Distribution Factor or the percent of commuters on or under bridges in the Census tract.

12.2 Description of Methodology

The casualty module is complementary to the concepts put forward by other models (Coburn and Spence, 1992; Murakami, 1992; Shiono et al., 1991a, b). The Coburn and Spence model uses a similar four-level injury severity scale (light injuries, hospitalized injuries, life threatening injuries, and deaths) and underlying concepts associated with building collapse. However, it is not in event tree format and does not account for non-collapse (damage) related casualties, nor does it account for the population outdoors at the time of earthquake. The Murakami model is an event tree model that includes only fatalities caused by collapsed buildings and does not account for lesser injuries. Shiono's model is similar to the other two models and only estimates fatalities. The methodology as implemented takes into account a wider range of causal relationships in the casualty modeling. It is an extension of the model proposed by Stojanovski and Dong (1994).

Casualties caused by a postulated earthquake can be modeled by developing a tree of events leading to their occurrence. As with any event tree, the earthquake-related casualty event tree begins with an initiating event (the earthquake scenario) and follows the possible course of events leading to loss of life or injuries. The logic of its construction is forward (inductive). At each node of the tree, the (node branching) question is: What happens if the preceding event leading to the node occurs? The answers to this question are represented by the branches of the tree. The number of branches from any node is equal to the number of answers defined for the node branching question. Each branch of the tree is assigned a probability of occurrence. As noted earlier, data for earthquake-related casualties are relatively scarce, particularly for U.S. earthquakes. Therefore, to some extent the casualty rates are inferred from the available data and combined with expert opinion.

As an example, the expected number of occupants killed in a building during a given earthquake could be simulated with an event tree as shown in Figure 12-1. For illustrative purposes, it contains only "occupants killed” as events of interest and does not depict lesser severities of casualties. Evaluation of the branching probabilities constitutes the main effort in the earthquake casualty modeling. Assuming that all the branching probabilities are known or inferred, the probability of an occupant being killed (Pkilled) is given in Equation 12-2.

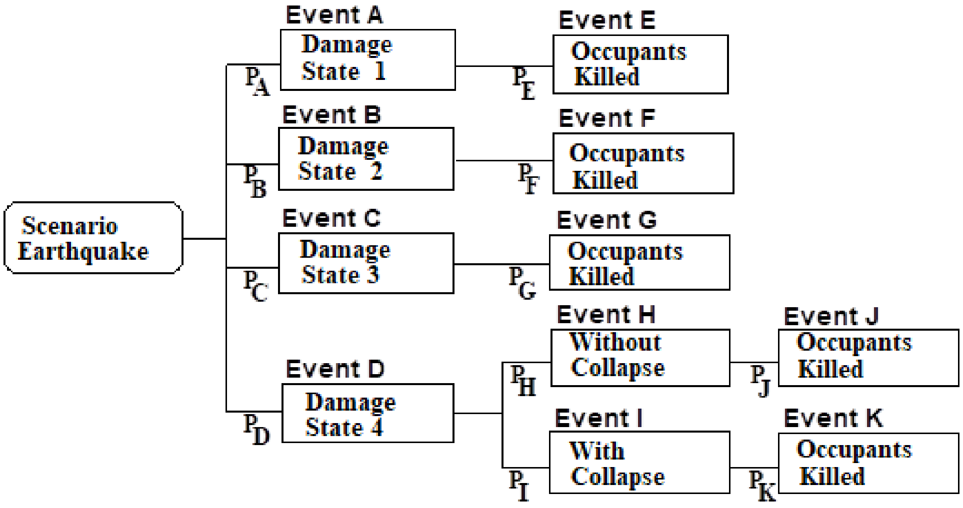


Figure 12-1 Example Casualty Event Tree for Fatalities

Equation 12-2

$$P_{\text{killed}} = (P_A * P_E) + (P_B * P_F) + (P_C * P_G) + P_D * \left[\left(P_H * P_J\right) + (P_I * P_K)\right]$$

By introducing the substitutions given in Equation 12-3 and Equation 12-4, Equation 12-2 can be re-written as simplified to Equation 12-5.

Equation 12-3

$$P_{\text{killed} \ | \ \text{Collapse}} = P_D * P_I * P_K$$

Equation 12-4

$$P_{\text{killed} \ | \ \text{No Collapse}} = (P_A * P_E) + (P_B * P_F) + (P_C * P_G) + \left(P_D * P_H * P_J\right)$$

Equation 12-5

$$P_{\text{killed}} = P_{\text{killed} \ | \ \text{Collapse}} + P_{\text{killed} \ | \ \text{No Collapse}}$$

The first term in Equation 12-5 represents casualties associated with building collapse. The second term represents casualties associated with the level of non-collapse damage the building sustains during the earthquake. Records from past earthquakes show that for different regions in the world, with different kinds of construction, there are different threshold intensities at which the first term begins to dominate. For intensities below that shaking level, casualties are primarily damage or non-collapse related. For intensities above that level, the collapse, often of only a few structures, may control the casualty pattern.

The expected number of occupants killed is the product of the number of occupants of the building at the time of earthquake and the probability of an occupant being killed, as given in Equation 12-6.

Equation 12-6

$$EN_{\text{Occupants Killed}} = N_{\text{Occupants}} * P_{\text{killed}}$$

Figure 12-2 presents a more complete earthquake-related casualty event tree for indoor casualties, which is used in the methodology. The branching probabilities are not shown in the figure in order to make the module presentation simpler. The events are represented with rectangular boxes, with a short event or state description given in each box. The symbol "<" attached to an event box means that branching out from that node is identical to branching from other nodes for the same category event (obviously, the appropriate probabilities would be different).

The event tree in Figure 12-2 is conceptual. It integrates several different event trees into one (light injuries, injuries requiring medical care, life threatening injuries, and deaths) for different occupancy types (residential, commercial, industrial, commuting) for people inside buildings. A similar event tree for outdoor casualties is used in the module. Casualty rates are different depending on the preceding causal events: specific building type, damage state, collapse, etc.

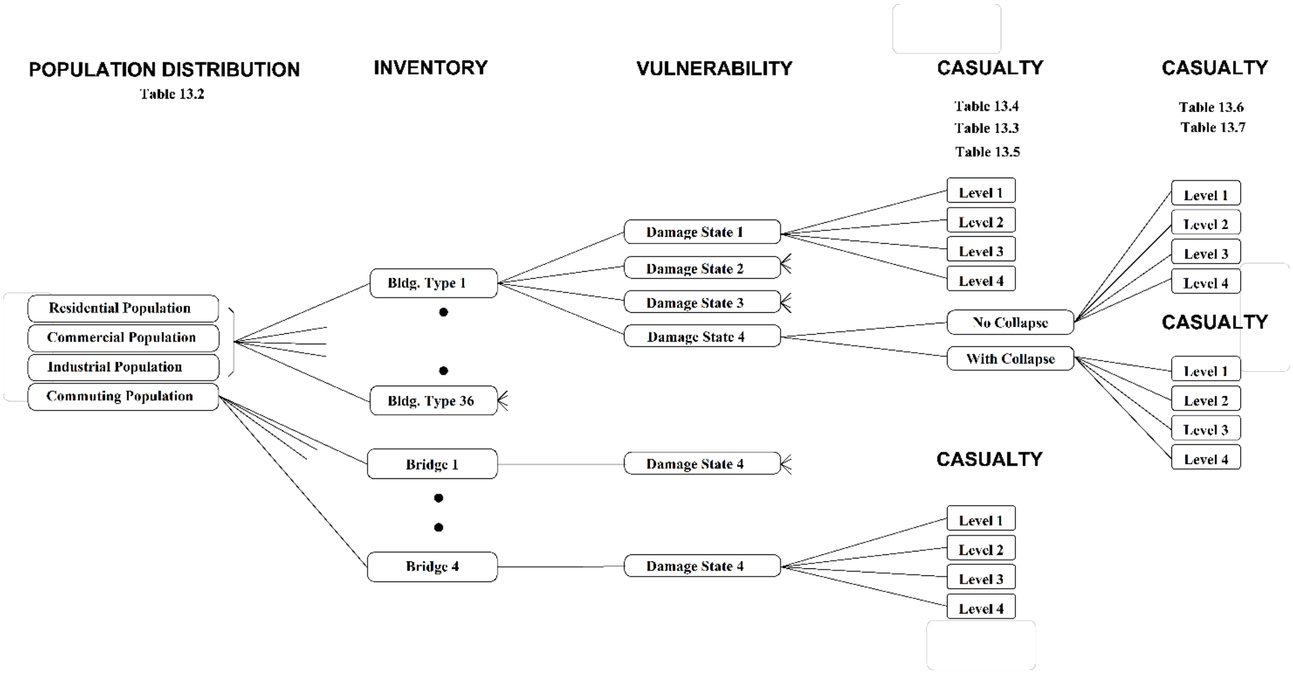


Figure 12-2 Indoor Casualty Event Tree Model

12.2.1 Casualty Rates

The casualty module is limited to the estimation of casualties caused by damage to buildings and bridges. Excluded are casualties or health effects not attributable to the immediate physical impact of the earthquake, such as heart attacks, psychological effects, toxic release, or injuries suffered during post-earthquake clean-up or construction activities. Outdoor casualties caused from collapsing masonry parapets, pieces of bearing walls, nonstructural wall panels, or from falling signs and other appendages are estimated and provided as a separate output of the module. The casualty rates used in the methodology are relatively uniform across building types for a given damage level, with differentiation to account for types of construction that pose higher-than-average hazards at Moderate damage levels (e.g., falling of pieces of unreinforced masonry) or at more severe levels (e.g., complete collapse of heavy concrete construction as compared to complete collapse of wood frame construction). For example, indoor casualty rates at Slight structural damage are the same for all specific building types. This is because at low levels of structural damage, casualties would most likely be caused by nonstructural components or contents, which do not vary greatly with specific building type.

Rates developed in the ATC-13 method (ATC, 1985) were evaluated and revised based on comparison with a limited amount of available historical data. General trends, such as 10 to 20 times as many non-hospitalized injuries as hospitalized injuries occurred in the 1994 Northridge earthquake (Durkin, 1995). The hospitalization rate (hospitalizations that did not result in death) for Los Angeles county of 1.56 per 100,000 population was four times the fatality rate of 0.37 per 100,000 (Peek-Asa et al., 1998). These trends were gathered from available data to provide guidance as to reasonable casualty rates. For several recent events, including the 1994 Northridge, 1989 Loma Prieta and 2001 Nisqually earthquakes, the casualties estimated by the methodology are a reasonable representation of the actual numbers observed (Comartin-Reis, 2001).

The user should keep in mind the intended use of the casualty estimates: to forecast the approximate magnitude of the number of injuries and fatalities. For example, an estimate that Severity 3 casualties are in the low hundreds, rather that several thousand, is useful to regional emergency medical authorities planning for a future event or an earthquake that has just occurred. However, for an event that has just occurred, there is no substitute for rapid surveys to compile actual figures. Note that "actual" casualty counts may still contain errors. Even for fatalities, data reported for actual fatalities are revised in the weeks and months following an earthquake.

The following casualty rates are defined by the methodology:

- Indoor Casualty Rates - Structural Damage
    - Casualty rates by specific building type for Slight, Moderate, and Extensive structural damage
    - Casualty rates by specific building type for Complete structural damage without collapse
    - Casualty rates by specific building type for Complete structural damage with collapse
- Outdoor Casualty Rates - Structural Damage
    - Casualty rates by specific building type for Moderate, Extensive, and Complete structural damage (the model assumes there are no outdoor casualties for buildings in the Slight structural damage state)
- Commuter Casualty Rates - Bridge Damage
    - Casualty rates by bridge type (i.e., major, continuous or single-span) for the Complete damage state

12.2.1.1 Indoor Casualty Rates

Table 12-3 through Table 12-7 define the indoor casualty rates by specific building type and damage state. It should be noted that only a portion of the buildings in the Complete damage state are considered to have collapsed. The collapse percentages for each specific building type are given in Section 5 and are summarized in Table 12-8. The percentages in the table are the estimated proportions of building square footage in the Complete damage state that are assumed to collapse for each specific building type.

Table 12-3 Indoor Casualty Rates by Specific Building Type for Slight Structural Damage

#	Building Type	Casualty Severity Level (%)			
		Severity 1	Severity 2	Severity 3	Severity 4
1	W1	0.05	0	0	0
2	W2	0.05	0	0	0
3	S1L	0.05	0	0	0
4	S1M	0.05	0	0	0
5	S1H	0.05	0	0	0
6	S2L	0.05	0	0	0
7	S2M	0.05	0	0	0
8	S2H	0.05	0	0	0
9	S3	0.05	0	0	0

#	Building Type	Casualty Severity Level (%)			
		Severity 1	Severity 2	Severity 3	Severity 4
10	S4L	0.05	0	0	0
11	S4M	0.05	0	0	0
12	S4H	0.05	0	0	0
13	S5L	0.05	0	0	0
14	S5M	0.05	0	0	0
15	S5H	0.05	0	0	0
16	C1L	0.05	0	0	0
17	C1M	0.05	0	0	0
18	C1H	0.05	0	0	0
19	C2L	0.05	0	0	0
20	C2M	0.05	0	0	0
21	C2H	0.05	0	0	0
22	C3L	0.05	0	0	0
23	C3M	0.05	0	0	0
24	C3H	0.05	0	0	0
25	PC1	0.05	0	0	0
26	PC2L	0.05	0	0	0
27	PC2M	0.05	0	0	0
28	PC2H	0.05	0	0	0
29	RM1L	0.05	0	0	0
30	RM1M	0.05	0	0	0
31	RM2L	0.05	0	0	0
32	RM2M	0.05	0	0	0
33	RM2H	0.05	0	0	0
34	URML	0.05	0	0	0
35	URMM	0.05	0	0	0
36	MH	0.05	0	0	0

Table 12-4 Indoor Casualty Rates by Specific Building Type for Moderate Structural Damage

#	Building Type	Casualty Severity Level (%)			
		Severity 1	Severity 2	Severity 3	Severity 4
1	W1	0.25	0.030	0	0
2	W2	0.20	0.025	0	0
3	S1L	0.20	0.025	0	0
4	S1M	0.20	0.025	0	0
5	S1H	0.20	0.025	0	0
6	S2L	0.20	0.025	0	0

#	Building Type	Casualty Severity Level (%)			
		Severity 1	Severity 2	Severity 3	Severity 4
7	S2M	0.20	0.025	0	0
8	S2H	0.20	0.025	0	0
9	S3	0.20	0.025	0	0
10	S4L	0.25	0.030	0	0
11	S4M	0.25	0.030	0	0
12	S4H	0.25	0.030	0	0
13	S5L	0.20	0.025	0	0
14	S5M	0.20	0.025	0	0
15	S5H	0.20	0.025	0	0
16	C1L	0.25	0.030	0	0
17	C1M	0.25	0.030	0	0
18	C1H	0.25	0.030	0	0
19	C2L	0.25	0.030	0	0
20	C2M	0.25	0.030	0	0
21	C2H	0.25	0.030	0	0
22	C3L	0.20	0.025	0	0
23	C3M	0.20	0.025	0	0
24	C3H	0.20	0.025	0	0
25	PC1	0.25	0.030	0	0
26	PC2L	0.25	0.030	0	0
27	PC2M	0.25	0.030	0	0
28	PC2H	0.25	0.030	0	0
29	RM1L	0.20	0.025	0	0
30	RM1M	0.20	0.025	0	0
31	RM2L	0.20	0.025	0	0
32	RM2M	0.20	0.025	0	0
33	RM2H	0.20	0.025	0	0
34	URML	0.35	0.400	0.001	0.001
35	URMM	0.35	0.400	0.001	0.001
36	MH	0.25	0.030	0	0

Table 12-5 Indoor Casualty Rates by Specific Building Type for Extensive Structural Damage

#	Building Type	Casualty Severity Level (%)			
		Severity 1	Severity 2	Severity 3	Severity 4
1	W1	1	0.1	0.001	0.001
2	W2	1	0.1	0.001	0.001
3	S1L	1	0.1	0.001	0.001
4	S1M	1	0.1	0.001	0.001

#	Building Type	Casualty Severity Level (%)			
		Severity 1	Severity 2	Severity 3	Severity 4
5	S1H	1	0.1	0.001	0.001
6	S2L	1	0.1	0.001	0.001
7	S2M	1	0.1	0.001	0.001
8	S2H	1	0.1	0.001	0.001
9	S3	1	0.1	0.001	0.001
10	S4L	1	0.1	0.001	0.001
11	S4M	1	0.1	0.001	0.001
12	S4H	1	0.1	0.001	0.001
13	S5L	1	0.1	0.001	0.001
14	S5M	1	0.1	0.001	0.001
15	S5H	1	0.1	0.001	0.001
16	C1L	1	0.1	0.001	0.001
17	C1M	1	0.1	0.001	0.001
18	C1H	1	0.1	0.001	0.001
19	C2L	1	0.1	0.001	0.001
20	C2M	1	0.1	0.001	0.001
21	C2H	1	0.1	0.001	0.001
22	C3L	1	0.1	0.001	0.001
23	C3M	1	0.1	0.001	0.001
24	C3H	1	0.1	0.001	0.001
25	PC1	1	0.1	0.001	0.001
26	PC2L	1	0.1	0.001	0.001
27	PC2M	1	0.1	0.001	0.001
28	PC2H	1	0.1	0.001	0.001
29	RM1L	1	0.1	0.001	0.001
30	RM1M	1	0.1	0.001	0.001
31	RM2L	1	0.1	0.001	0.001
32	RM2M	1	0.1	0.001	0.001
33	RM2H	1	0.1	0.001	0.001
34	URML	2	0.2	0.002	0.002
35	URMM	2	0.2	0.002	0.002
36	MH	1	0.1	0.001	0.001

Table 12-6 Indoor Casualty Rates by Specific Building Type for Complete Structural Damage (No Collapse)

#	Building Type	Casualty Severity Level (%)			
		Severity 1	Severity 2	Severity 3	Severity 4
1	W1	5	1	0.01	0.01
2	W2	5	1	0.01	0.01
3	S1L	5	1	0.01	0.01
4	S1M	5	1	0.01	0.01
5	S1H	5	1	0.01	0.01
6	S2L	5	1	0.01	0.01
7	S2M	5	1	0.01	0.01
8	S2H	5	1	0.01	0.01
9	S3	5	1	0.01	0.01
10	S4L	5	1	0.01	0.01
11	S4M	5	1	0.01	0.01
12	S4H	5	1	0.01	0.01
13	S5L	5	1	0.01	0.01
14	S5M	5	1	0.01	0.01
15	S5H	5	1	0.01	0.01
16	C1L	5	1	0.01	0.01
17	C1M	5	1	0.01	0.01
18	C1H	5	1	0.01	0.01
19	C2L	5	1	0.01	0.01
20	C2M	5	1	0.01	0.01
21	C2H	5	1	0.01	0.01
22	C3L	5	1	0.01	0.01
23	C3M	5	1	0.01	0.01
24	C3H	5	1	0.01	0.01
25	PC1	5	1	0.01	0.01
26	PC2L	5	1	0.01	0.01
27	PC2M	5	1	0.01	0.01
28	PC2H	5	1	0.01	0.01
29	RM1L	5	1	0.01	0.01
30	RM1M	5	1	0.01	0.01
31	RM2L	5	1	0.01	0.01
32	RM2M	5	1	0.01	0.01
33	RM2H	5	1	0.01	0.01
34	URML	10	2	0.02	0.02
35	URMM	10	2	0.02	0.02
36	MH	5	1	0.01	0.01

#	Building Type	Casualty Severity Level (%)			
		Severity 1	Severity 2	Severity 3	Severity 4
B1	Major Bridge	17	20	37	7
B2	Continuous Bridge	17	20	37	7
B3	S.S. Bridge	5	25	20	5

Table 12-7 Indoor Casualty Rates by Specific Building Type for Complete Structural Damage (With Collapse)

#	Building Type	Casualty Severity Level (%)			
		Severity 1	Severity 2	Severity 3	Severity 4
1	W1	40	20	3	5
2	W2	40	20	5	10
3	S1L	40	20	5	10
4	S1M	40	20	5	10
5	S1H	40	20	5	10
6	S2L	40	20	5	10
7	S2M	40	20	5	10
8	S2H	40	20	5	10
9	S3	40	20	3	5
10	S4L	40	20	5	10
11	S4M	40	20	5	10
12	S4H	40	20	5	10
13	S5L	40	20	5	10
14	S5M	40	20	5	10
15	S5H	40	20	5	10
16	C1L	40	20	5	10
17	C1M	40	20	5	10
18	C1H	40	20	5	10
19	C2L	40	20	5	10
20	C2M	40	20	5	10
21	C2H	40	20	5	10
22	C3L	40	20	5	10
23	C3M	40	20	5	10
24	C3H	40	20	5	10
25	PC1	40	20	5	10
26	PC2L	40	20	5	10
27	PC2M	40	20	5	10
28	PC2H	40	20	5	10
29	RM1L	40	20	5	10
30	RM1M	40	20	5	10

#	Building Type	Casualty Severity Level (%)			
		Severity 1	Severity 2	Severity 3	Severity 4
31	RM2L	40	20	5	10
32	RM2M	40	20	5	10
33	RM2H	40	20	5	10
34	URML	40	20	5	10
35	URMM	40	20	5	10
36	MH	40	20	3	5

Table 12-8 Collapse Rates by Specific Building Type for Complete Structural Damage

#	Specific Building Type	Probability of Collapse Given A Complete Damage State*
1	W1	3.0%
2	W2	3.0%
3	S1L	8.0%
4	S1M	5.0%
5	S1H	3.0%
6	S2L	8.0%
7	S2M	5.0%
8	S2H	3.0%
9	S3	3.0%
10	S4L	8.0%
11	S4M	5.0%
12	S4H	3.0%
13	S5L	8.0%
14	S5M	5.0%
15	S5H	3.0%
16	C1L	13.0%
17	C1M	10.0%
18	C1H	5.0%
19	C2L	13.0%
20	C2M	10.0%
21	C2H	5.0%
22	C3L	15.0%
23	C3M	13.0%
24	C3H	10.0%
25	PC1	15.0%
26	PC2L	15.0%
27	PC2M	13.0%
28	PC2H	10.0%

#	Specific Building Type	Probability of Collapse Given A Complete Damage State*
29	RM1L	13.0%
30	RM1M	10.0%
31	RM2L	13.0%
32	RM2M	10.0%
33	RM2H	5.0%
34	URML	15.0%
35	URMM	15.0%
36	MH	3.0%

** See Section 5 for the derivation of these values*

12.2.1.2 Outdoor Casualty Rates

Experience in earthquakes overseas and in the United States shows that a number of casualties occur outside buildings due to falling materials. People that are outside, but close to buildings could be hurt by structural or nonstructural elements falling from the buildings. Examples are damaged parapets, loosened bricks, broken window glass, signage, awnings, or nonstructural panels. In the 1987 Whittier Narrows earthquake, a student at California State University, Los Angeles was killed when a concrete panel fell from a parking structure. In the 1983 Coalinga earthquake, one person was severely injured when the façade of a building collapsed onto the sidewalk and two people sitting in a parked car were hit by bricks from a collapsing building. Five people in San Francisco died when a brick wall collapsed onto their cars during the 1989 Loma Prieta earthquake. In the United States, casualties due to outdoor falling hazards have been caused primarily by falling unreinforced masonry, which may cause damage to adjoining buildings or fall directly on people outside the building and result in casualties.

People outside of buildings are less likely to be injured or killed than those inside buildings. For example, in the 1989 Loma Prieta earthquake, of the 185 people who were injured or killed in Santa Cruz County, 20 people were outside and 1 was in a car (Wagner, 1996). An epidemiological study of casualties in the Loma Prieta earthquake indicates that injury risk in Santa Cruz County was 2.87 times higher for those in a building versus outside of a building (Jones et al., 1994). Note that the sample of residents surveyed was located mostly in suburban and rural surroundings. It is possible for a given earthquake to occur at a time of day and in a densely built-up locale where relatively more exterior casualties would occur. The Hazus Methodology is based on probable outcomes, not the "worst case scenario."

This module attempts to account for casualties due to falling hazards, particularly with respect to areas where people congregate, such as sidewalks. To accomplish this, the number of people on sidewalks or similar exterior areas is estimated according to Table 12-2. The table is designed to prevent double counting casualties from outdoor falling hazards with building occupant casualties.

The module for estimating outdoor casualties is an event tree similar to that for indoor casualties. One difference is that the outdoor casualty event tree does not branch into collapse or no collapse for the Complete damage state. Instead, the four severities of casualties depend only on the damage state of the building. The justification for this simplification is that people outside of buildings are much less likely to be trapped by collapsed floors. Another difference is that the module assumes that Slight structural damage does not generate outdoor casualties. This is equivalent to eliminating Damage State 1 from the event tree in Figure 12-2. The probabilities for the event tree branches (outdoor casualty rates by specific building type) are in Table 12-9 through Table 12-11.

Table 12-9 Outdoor Casualty Rates by Specific Building Type for Moderate Structural Damage

#	Building Type	Casualty Severity Level (%)			
		Severity 1	Severity 2	Severity 3	Severity 4
1	W1	0.05	0.005	0.0001	0.0001
2	W2	0.05	0.005	0	0
3	S1L	0.05	0.005	0	0
4	S1M	0.05	0.005	0	0
5	S1H	0.05	0.005	0	0
6	S2L	0.05	0.005	0	0
7	S2M	0.05	0.005	0	0
8	S2H	0.05	0.005	0	0
9	S3	0	0	0	0
10	S4L	0.05	0.005	0	0
11	S4M	0.05	0.005	0	0
12	S4H	0.05	0.005	0	0
13	S5L	0.05	0.005	0	0
14	S5M	0.05	0.005	0	0
15	S5H	0.05	0.005	0	0
16	C1L	0.05	0.005	0	0
17	C1M	0.05	0.005	0	0
18	C1H	0.05	0.005	0	0
19	C2L	0.05	0.005	0	0
20	C2M	0.05	0.005	0	0
21	C2H	0.05	0.005	0	0
22	C3L	0.05	0.005	0	0
23	C3M	0.05	0.005	0	0
24	C3H	0.05	0.005	0	0
25	PC1	0.05	0.005	0	0
26	PC2L	0.05	0.005	0	0
27	PC2M	0.05	0.005	0	0
28	PC2H	0.05	0.005	0	0
29	RM1L	0.05	0.005	0	0
30	RM1M	0.05	0.005	0	0
31	RM2L	0.05	0.005	0	0
32	RM2M	0.05	0.005	0	0
33	RM2H	0.05	0.005	0	0
34	URML	0.15	0.015	0.0003	0.0003

#	Building Type	Casualty Severity Level (%)			
		Severity 1	Severity 2	Severity 3	Severity 4
35	URMM	0.15	0.015	0.0003	0.0003
36	MH	0	0	0	0

** The model assumes that there are no outdoor casualties for Slight structural damage.*

Table 12-10 Outdoor Casualty Rates by Specific Building Type for Extensive Structural Damage

#	Building Type	Casualty Severity Level (%)			
		Severity 1	Severity 2	Severity 3	Severity 4
1	W1	0.3	0.03	0.0003	0.0003
2	W2	0.3	0.03	0.0003	0.0003
3	S1L	0.1	0.01	0.0001	0.0001
4	S1M	0.2	0.02	0.0002	0.0002
5	S1H	0.3	0.03	0.0003	0.0003
6	S2L	0.1	0.01	0.0001	0.0001
7	S2M	0.2	0.02	0.0002	0.0002
8	S2H	0.3	0.03	0.0003	0.0003
9	S3	0	0	0	0
10	S4L	0.1	0.01	0.0001	0.0001
11	S4M	0.2	0.02	0.0002	0.0002
12	S4H	0.3	0.03	0.0003	0.0003
13	S5L	0.2	0.02	0.0002	0.0002
14	S5M	0.4	0.04	0.0004	0.0004
15	S5H	0.6	0.06	0.0006	0.0006
16	C1L	0.1	0.01	0.0001	0.0001
17	C1M	0.2	0.02	0.0002	0.0002
18	C1H	0.3	0.03	0.0003	0.0003
19	C2L	0.1	0.01	0.0001	0.0001
20	C2M	0.2	0.02	0.0002	0.0002
21	C2H	0.3	0.03	0.0003	0.0003
22	C3L	0.2	0.02	0.0002	0.0002
23	C3M	0.4	0.04	0.0004	0.0004
24	C3H	0.6	0.06	0.0006	0.0006
25	PC1	0.2	0.02	0.0002	0.0002
26	PC2L	0.1	0.01	0.0001	0.0001
27	PC2M	0.2	0.02	0.0002	0.0002
28	PC2H	0.3	0.03	0.0003	0.0003
29	RM1L	0.2	0.02	0.0002	0.0002
30	RM1M	0.3	0.03	0.0003	0.0003
31	RM2L	0.2	0.02	0.0002	0.0002

#	Building Type	Casualty Severity Level (%)			
		Severity 1	Severity 2	Severity 3	Severity 4
32	RM2M	0.3	0.03	0.0003	0.0003
33	RM2H	0.4	0.04	0.0004	0.0004
34	URML	0.6	0.06	0.0006	0.0006
35	URMM	0.6	0.06	0.0006	0.0006
36	MH	0	0	0	0

Table 12-11 Outdoor Casualty Rates by Specific Building Type for Complete Structural Damage

#	Building Type	Casualty Severity Level (%)			
		Severity 1	Severity 2	Severity 3	Severity 4
1	W1	2	0.5	0.1	0.05
2	W2	2	0.5	0.1	0.05
3	S1L	2	0.5	0.1	0.1
4	S1M	2.2	0.7	0.2	0.2
5	S1H	2.5	1	0.3	0.3
6	S2L	2	0.5	0.1	0.1
7	S2M	2.2	0.7	0.2	0.2
8	S2H	2.5	1	0.3	0.3
9	S3	0.01	0.001	0.001	0.01
10	S4L	2	0.5	0.1	0.1
11	S4M	2.2	0.7	0.2	0.2
12	S4H	2.5	1	0.3	0.3
13	S5L	2.7	1	0.2	0.3
14	S5M	3	1.2	0.3	0.4
15	S5H	3.3	1.4	0.4	0.6
16	C1L	2	0.5	0.1	0.1
17	C1M	2.2	0.7	0.2	0.2
18	C1H	2.5	1	0.3	0.3
19	C2L	2	0.5	0.1	0.1
20	C2M	2.2	0.7	0.2	0.2
21	C2H	2.5	1	0.3	0.3
22	C3L	2.7	1	0.2	0.3
23	C3M	3	1.2	0.3	0.4
24	C3H	3.3	1.4	0.4	0.6
25	PC1	2	0.5	0.1	0.1
26	PC2L	2.7	1	0.2	0.3
27	PC2M	3	1.2	0.3	0.4
28	PC2H	3.3	1.4	0.4	0.6
29	RM1L	2	0.5	0.1	0.1

#	Building Type	Casualty Severity Level (%)			
		Severity 1	Severity 2	Severity 3	Severity 4
30	RM1M	2.2	0.7	0.2	0.2
31	RM2L	2	0.5	0.1	0.1
32	RM2M	2.2	0.7	0.2	0.2
33	RM2H	2.5	1	0.3	0.3
34	URML	5	2	0.4	0.6
35	URMM	5	2	0.4	0.6
36	MH	0.01	0.001	0.001	0.01

12.2.1.3 Casualty Rates Resulting from Bridge Collapse

The module estimates casualties for people either on or under bridges that experience Complete damage. The number of people on or under bridges is calculated from Table 12-2 and Equation 12-1. Casualty rates for bridges in the Complete damage state are included in Table 12-6.

12.2.1.4 Single Span Bridges

One reference that reports on many aspects of a single span bridge collapse is "Loma Prieta Earthquake October 17, 1989; I-80 San Francisco - Oakland Bay Bridge, Closure Span Collapse," published by the California Highway Patrol (Golden Gate MAIT, 1990a). This document systematically reports on the facts related to the collapse of one of the spans of the bridge. The only fatality was recorded approximately half an hour after the event, when a car drove into the gap created by the collapse.

Estimates of casualty rates for single span (SS) bridges are provided in Table 12-6 (Casualty Rates for Complete Structural damage only). Lack of data did not allow for similar inferences for other damage states.

12.2.1.5 Major and Continuous Bridges

A second report published by the California Highway Patrol "Loma Prieta Earthquake October 17, 1989; I-880 Cypress Street Viaduct Structure Collapse," (Golden Gate MAIT, 1990b) summarizes many aspects of a continuous (major) bridge collapse. This reference systematically reports facts related to the collapse of the structure. Most of the injuries and fatalities occurred on the lower northbound deck as a consequence of the collapse of the upper deck onto the lower deck. A significant portion of injuries and fatalities also occurred among the people driving on the upper southbound deck. A small portion of casualties resulted from vehicles on the surface streets adjacent to the collapsed structure.

For casualty rates for major and continuous bridges, the methodology has used casualty statistics on the upper deck of the Cypress Viaduct and on the adjacent surface streets. Double decker highway bridges are unusual and are not specifically modeled in Hazus. Thus, casualty statistics associated with the vehicles on the lower deck are not considered representative.

12.3 Guidance for Estimates Using Advanced Data and Models

In the absence of adequate U.S.-specific casualty data resulting from structural collapse, international data on the casualty rates for specific structural types may be used. If overseas casualty rates are used, U.S. construction practices, design, and construction quality would have to be reflected in the appropriate region-specific fragility curves. If average worldwide casualty statistics or data from one or a few other countries are to be used for collapse-related casualty modeling in the United States, special attention must be given to the relationship between the U.S. structural types and the structural types represented by these other data sets. Also, appropriate mapping between injury classification scales must be established. Finally, it is possible that differing levels of earthquake preparedness, such as the effectiveness of the emergency medical system, and the training of the public in personal protective measures, such as "duck and cover," might cause U.S. casualty rates to differ from those overseas. This is unlikely to be a significant factor in cases of collapse and presently there are no data available on these types of issues.

Published data on collapse-related casualty rates is limited. Noji (1990) provided this type of data for stone masonry and precast concrete buildings based on data from the 1988 Armenia earthquake. Murakami (1992) used these rates in a model that simulated the fatalities from the same event. Durkin and Murakami (1989) reported casualty rates for two reinforced concrete buildings collapsed during the 1985 Mexico and 1986 San Salvador earthquakes. Shiono et al. (1991a, b) provided fatality rates after collapse for most common worldwide structural types. Also, Coburn and Spence (1992) have summarized approximate casualty rates for masonry and reinforced concrete structures based on worldwide data.

The casualty patterns for people who evacuate collapsed buildings, either before or immediately after the collapse, are more difficult to quantify. Statistical data on these casualty patterns is lacking, since in most post-earthquake reconnaissance efforts these injuries are not distinguished from other causes of injuries. In some cases, the lighter injuries may not be reported. It can be assumed that those who managed to evacuate are neither killed nor receive life threatening injuries. It is assumed that 50% of the occupants of the first floor manage to evacuate.

Section 13. Direct Social Losses – Population Displacement and Shelter Needs

Earthquakes can cause loss of function or habitability of buildings that contain housing units, displacing the households that reside there. Displaced households may need short-term shelter provided by public agencies or relief organizations such as the Red Cross, Salvation Army, and others, or alternative shelter, provided by family, friends, or by renting apartments or houses. For housing units where repair takes longer than a few weeks, long-term alternative housing can be accommodated by importing mobile homes, occupancy of vacant units, net emigration from the impacted area, and, eventually, by the repair or reconstruction of new public and private housing. While the number of people seeking short-term public shelter is of great concern to emergency response organizations, the longer-term impacts on the housing stock, which are not currently modeled (see Section 13.4.2). are also of concern to local governments, such as cities and counties.

13.1 Scope

The shelter module provides two estimates:

- The number of displaced households (due to loss of habitability)
- The number of people requiring publicly-provided short-term shelter

Loss of habitability is calculated directly from damage to the residential building inventory. While loss of water and power may also impact displacement, these factors are not currently considered in the Hazus Methodology. The methodology for calculating short-term shelter requirements recognizes that only a portion of those displaced from their homes will seek public shelter, and that some people will seek shelter even though their residence may have no or insignificant damage.

Households may also be displaced as result of fire following earthquake, inundation (or the threat of inundation) due to dam failure, and by significant hazardous waste releases. The Hazus shelter module does not specifically account for these issues, but an approximate estimate of displacement due to fire can be obtained by overlaying the residential inventory and population exposure in affected Census tracts with areas of fire damage. The hazardous materials module is confined to identifying locations of hazardous materials and has no methodology provided for calculations of damage or loss. If the characteristics of the Study Region give the user cause for concern about the possibility of housing loss from fire, dam failure, or hazardous materials, it would be advisable to initiate specific studies directed towards the problem, as a Level 2/3 Advanced analysis.

13.2 Displaced Households

The total number of uninhabitable dwelling units (#UNU) for each Census tract of the Study Region is the output of this portion of the module. In addition, by applying an occupancy rate (households vs. dwelling units), the module converts the habitability data to the number of displaced households. The number of displaced households will be used in Section 13.3 to estimate the short-term shelter needs.

13.2.1 Input Requirements

The following inputs at the Census tract level are required to compute the number of uninhabitable dwelling units and the number of displaced households. The total number of dwelling units or households is provided in the baseline inventory data (refer to the *Hazus Inventory Technical Manual* for additional information). The user can update these demographic data if improved or updated information is available.

- Demographic data
    - Total Number of Single-Family Dwelling Units (#SFU), including mobile homes
    - Total Number of Multi-Family Dwelling Units (#MFU)
    - Total Number of Households (#HH)
- Census tract level results from the General Building Stock Direct Physical Damage Module (see Section 5)
    - Damage state probability for Moderate structural damage in the single-family residential occupancy classes (%SFM).
    - Damage state probability for Extensive structural damage state in the single-family residential occupancy classes (%SFE).
    - Damage state probability for Complete structural damage state in the single-family residential occupancy classes (%SFC).
    - Damage state probability for Moderate structural damage state in the multi-family residential occupancy classes (%MFM).
    - Damage state probability for Extensive structural damage state in the multi-family residential occupancy classes (%MFE).
    - Damage state probability for Complete structural damage state in the multi-family residential occupancy classes (%MFC).

13.2.2 Description of Methodology

The estimated number of uninhabitable dwelling units is calculated by combining a) the number of uninhabitable dwelling units due to actual structural damage and b) the approximate number of damaged units that are perceived to be uninhabitable by their occupants. Based on comparisons with previous work (Perkins, 1992; Perkins and Harrald et al., unpublished), the methodology assumes all dwelling units located in buildings that are in the Complete damage state to be uninhabitable. In addition, some percentage of dwelling units in multi-family structures in the Moderate and Extensive damage states may also be considered uninhabitable due to the fact that renters perceive some moderately damaged rental property as uninhabitable; baseline percentages are set to 0% for Moderate damage and 90% for Extensive damage (see Table 13-1), but these values may be edited by the user. On the other hand, those living in single-family homes are much more likely to tolerate damage and continue to live in their home Research has shown a much clearer relationship between the red-, yellow-, and green-tagging assigned by building inspectors and perceived habitability than between damage state and perceived habitability (Perkins and Harrald et al., unpublished). Red- and yellow-tagged multi-family dwellings are considered uninhabitable, while only red-tagged single-family homes are considered uninhabitable.

By applying an occupancy rate (households vs. dwelling units), the total number of displaced households (#DH) is calculated using the following equations. The baseline probabilities or weighting factor values for single- and multi-family residences and damage states are provided in Table 13-1.

Equation 13-1

$$\%SF = W_{SFM} * \%SFM + W_{SFE} * \%SFE + W_{SFC} * \%SFC$$

Equation 13-2

$$\%MF = W_{MFM} * \%MFM + W_{MFE} * \%MFE + W_{MFC} * \%MFC$$

Equation 13-3

$$\#DH = (\#SFU * \%SF + \#MFU * \%MF) * \left(\frac{\#HH}{\#SFU + \#MFU}\right)$$

Where:

%SF	is the percent of single-family dwelling units that are uninhabitable
%MF	is the percent of multi-family dwelling units that are uninhabitable

Table 13-1 Default Values for Displaced Household Damage State Weighting Factors

Weighting Factor	Default Value
Single-family, Moderate damage (W_{SFM})	0.0
Single-family, Extensive damage (W_{SFE})	0.0
Single-family, Complete damage (W_{SFC})	1.0
Multi-family, Moderate damage (W_{MFM})	0.0
Multi-family, Extensive damage (W_{MFE})	0.9
Multi-family, Complete damage (W_{MFC})	1.0

13.3 Short-term Shelter Needs

All households living in uninhabitable dwellings are expected to seek alternative shelter. Many displaced individuals will stay with friends, relatives, or in the family car. Some will stay in public shelters provided by the Red Cross or others, or rent a motel or an apartment. This methodology estimates the number of displaced persons seeking public shelter. In addition, observations from past disasters show that approximately 80% of the pre-disaster homeless will also seek public shelter. Data from the 1994 Northridge earthquake indicates that approximately one-third of those in public shelters came from residences with little or no structural damage. The number of displaced persons could be increased by up to 50% to account for "perceived" structural damage as well as lack of water and power.

13.3.1 Input Requirements

The inputs required to estimate short-term shelter needs are obtained from the displaced household calculations described in Section 13.2 and from the baseline demographic data (refer to the *Hazus Inventory Technical Manual* for additional information). As with the entire methodology, these demographic data can be modified with improved or updated user information. The inputs listed below are the required demographic data input for the short-term shelter estimates:

- Number of people in Census tract (POP)
- Number of Households (#HH)
- Percentage of households whose income is under \$10,000 (HI_1)
- Percentage of households whose income is \$10,001 to \$20,000 (HI_2)
- Percentage of households whose income is \$20,001 to \$30,000 (HI_3)
- Percentage of households whose income is \$30,001 to \$40,000 (HI_4)
- Percentage of households whose income is over \$40,000 (HI_5)
- Percentage of white households (HE_1)
- Percentage of black households (HE_2)
- Percentage of Hispanic households (HE_3)
- Percentage of Native American households (HE_4)
- Percentage of Asian households (HE_5)
- Percentage of households owned by householder (HO_1)
- Percentage of households rented by householder (HO_2)
- Percentage of population under 16 years old (HA_1)
- Percentage of population between 16 and 65 years old (HA_2)
- Percentage of population over 65 years old (HA_3)

13.3.2 Description of Methodology

Those seeking public shelter can be estimated from experience in past disasters, including both hurricanes and earthquakes. Those seeking shelter typically have very low incomes, for these families have fewer options. In addition, they tend to be over the age of 65 or have young children. Finally, even given similar incomes, populations from Central America and Mexico tend to be more concerned about reoccupying buildings than other ethnic groups. This tendency appears to be because of the fear of collapsed buildings instilled from past disastrous Latin American earthquakes. For each Census tract, the number of people who will utilize public short-term shelter can be calculated using the following relationship.

Equation 13-4

$$\#\mathrm{STP} = \sum_{i=1}^{5}\sum_{j=1}^{5}\sum_{k=1}^{5}\sum_{l=1}^{5}\left(\alpha_{ijkl} * \left(\frac{\#\mathrm{DH} * \mathrm{POP}}{\#\mathrm{HH}}\right) * \mathrm{HI}_i * \mathrm{HE}_j * \mathrm{HO}_k * \mathrm{HA}_l\right)$$

Where:

#STP	is the number of people requiring public short-term shelter
α_{ijkl}	is a constant defined by Equation 13-5
#DH	is the number of displaced households calculated from Equation 13-3
POP	is the population in the Census tract
#HH	is the number of Households in the Census tract

HI_i is the percentage of population in Income Class i

HE_j is the percentage of population in Ethnicity Class j

HO_k is the percentage of population in Ownership Class k

HA_l is the percentage of population in Age Class l

The value of the constant α_{ijkl} (i.e., the percentage of each category that will seek shelter) can be calculated as shown in Equation 13-5 using a combination of shelter category "weights" (Table 13-2) which sum to 1.00, and assigning a relative modification factor (Table 13-3) for each subcategory. In the methodology, baseline values for the weighting factors for ownership (OW) and age (AW) are zero.

The weighting and modification factors given in Table 13-2 and Table 13-3 respectively, were originally developed by George Washington University under contract with the the Red Cross and are based on expert opinion (Harrald et al.,1992). Additional data collected from over 200 victims of the Northridge earthquake disaster were analyzed and used to finalize these constants (Harrald et al., 1994). The modification factors provided in Table 13-3 represent the mean of the George Washington University modification factors described in these two reports. Data for Native American populations are extremely scarce. Some information from Alaskan disasters indicates that the factor for those seeking shelter is similar to both white and Asian populations.

Equation 13-5

$$\alpha_{ijkl} = (IW * IM_i) + \left(EW * EM_j\right) + (OW * OM_k) + (AW * AM_l)$$

Table 13-2 Default Values for Shelter Category Weighting Factors

Class	Weighting Factor	Default Value
IW	Income Weighting Factor	0.73
EW	Ethnicity Weighting Factor	0.27
OW	Ownership Weighting Factor	0.0
AW	Age Weighting Factor	0.0

Table 13-3 Default Values for Shelter Modification Factors

Class	Modification Factor	Default Value
Income		
IM_1	Household Income < \$10,000	0.62
IM_2	\$10,000 < Household Income < \$20,000	0.42
IM_3	\$20,000 < Household Income < \$30,000	0.29
IM_4	\$30,000 < Household Income < \$40,000	0.22
IM_5	Household Income > \$40,000	0.13
Ethnicity		
EM_1	White	0.24
EM_2	Black	0.48
EM_3	Hispanic	0.47
EM_4	Asian	0.26
EM_5	Native American	0.26

Class	Modification Factor	Default Value
Ownership		
OM_1	Owner-occupied Dwelling Unit	0.40
OM_2	Renter-Occupied Dwelling Unit	0.40
Age		
AM_1	Population younger than 16 years old	0.40
AM_2	Population between 16 and 65 years old	0.40
AM_3	Population older than 65 years old	0.40

13.4 Guidance for Estimates Using Advanced Data and Models

13.4.1 Changes to Shelter Weighting and Modification Factors

In the methodology, weights can be added which account for age and ownership. As noted in Section 13.3.1, the required population distribution data are available. Remember that the weights must sum to 1.0. In the 1994 Northridge earthquake, young families tended to seek shelter in a larger proportion than other age groups, in part because of their lower per capita income. This result is consistent with data from hurricanes. In hurricanes and in the Northridge earthquake, elderly populations were also more likely to seek public shelter. The user should take special care when adding ownership weights to ensure that they are not double-counting, because the multi-family versus single-family issue has already been taken into account when estimating habitability (i.e., moderately damaged multi-family units are considered uninhabitable while moderately damaged single-family units are considered habitable).

Most recent earthquake disasters and hurricanes have occurred in warm weather areas. Informal shelter locations utilized included the family car and tents in the family's backyard. Should an earthquake occur in a colder climate, more people would probably find these alternate shelters unacceptable. In the methodology, the user is able to adjust the factors specifying the percentage of those displaced that seek public shelter (i.e., the shelter modification factors in Table 13-3). When making modifications for weather, be careful not to double count. The adjustment for this module should only take into account the larger percentage of those displaced that will seek public shelter (versus the family car or camping in one's backyard).

The Loma Prieta and Northridge earthquakes in California were not catastrophic events. Although many people were displaced in these earthquake disasters, the size of the area or the spottiness of the damage left people with more than minimal incomes the options of alternate shelters.

As noted above, populations from areas of Central America and Mexico tend to be more concerned about reoccupying buildings with insignificant or minor damage than other groups due to fear of collapsed buildings from past disastrous earthquakes experience in Latin America.

13.4.2 Guidance for Estimating Long-Term Housing Recovery

Although long-term housing requirements are not calculated by the methodology, the damage to residential units (calculated in the general building stock module) can be combined with relationships between damage and restoration times (see Section 11.2.4) to estimate the need for longer-term replacement housing. Longer-term needs are accommodated by importing mobile homes, reductions in the vacancy rates, net emigration from an area, and eventual repair or reconstruction of the housing units. Because replacement of permanent housing is subject to normal market and financial forces, low-income housing is generally the last type of housing to be replaced.

Based on experience in the 1989 Loma Prieta earthquake (Perkins, 1992) and preliminary analyses of the Northridge earthquake (Perkins et al., unpublished) housing recovery times span a wide range, and are typically far longer than might be estimated from typical planning rules of thumb, and longer than most commercial, industrial, and institutional recovery. Housing recovery tends to be dependent on the settlement of insurance claims, federal disaster relief, the effectiveness of the generally smaller contractors who are occupied with large quantities of residential projects, and the financial viability of the home or apartment owner, actions taken by state and local governments to expedite the process, and public support of reconstruction (such as the potential desire for historic preservation). The median recovery time figures for residential occupancies shown in Table 11-8 reflect these issues, but there may be significant variation in actual recovery times for individual buildings. Recovery times for non-wood frame multi-family housing, especially low-income single room occupancy buildings, should be measured in years.

Section 14. Indirect Economic Losses

The Hazus Indirect Economic Loss Module (IELM) was originally intended to operate using detailed, community-specific, commercially available economic data purchased from IMPLAN, to be supplied by the user. Initial Hazus releases included baseline IELM data representing generalized economy types (synthetic economies) that could be used in place of the more detailed IMPLAN data, but these have since been removed. Currently, both the IMPLAN and synthetic economy options in the IELM have been disabled. The technical background on the methods underpinning the IELM is available from the Hazus Help Desk (see Section 1.5) for users interested in implementing the indirect economic loss methodology.

Section 15. Annualized Losses

The primary source of earthquake hazard data used in the Hazus annualized loss assessment is the probabilistic seismic hazard curve data developed by the U.S. Geological Survey (USGS) for the National Seismic Hazard Mapping Program. These data have been processed for compatibility with Hazus (see Section 15.1). The curves specify ground motion, such as peak ground acceleration (PGA) and spectral acceleration (SA), as a function of the average annual frequency that a specified level of motion will be exceeded in an earthquake.

The USGS has developed these data for most regions of the U.S. (see Petersen et al., 2014). The hazard curves were developed for individual points in a uniform grid that covers all 50 states, Washington, D.C., and Puerto Rico.

The USGS hazard curves have been converted to a Hazus-compatible database of probabilistic ground shaking values (i.e., grid-based ground shaking data for each of eight return periods: 100, 250, 500, 750, 1,000, 1,500, ,2000, and 2,500 year return periods). Note that the recent increase in U.S. seismic hazards due to induced seismicity represented in the USGS one-year model (e.g., Petersen et al., 2017 and 2018) is not included. Probabilistic hazard data for Peak Ground Acceleration (PGA), spectral acceleration at 0.3 seconds ($SA_{0.3}$), and spectral acceleration at 1.0 second ($SA_{1.0}$) were processed for each grid cell for each of the eight different return periods.

Two versions of the USGS probabilistic hazard data grid are incorporated into Hazus:

- Users with no user-supplied soils data will automatically use the amplified version of the USGS 2014 probabilistic hazard data (see FEMA, 2017 for additional details). Amplification has been based on the USGS Vs30 site soil characterization data and the 2015 NEHRP site soil amplification factors (FEMA, 2015); straight-line interpolation was used to obtain intermediate values of amplification coefficients based on Vs30 values associated with each grid cell point. This represents an improvement over the prior approach, wherein probabilistic ground motion data in Hazus were amplified by the overly conservative Type D soft soil category.
- Users with custom/user-supplied soils data will use the non-amplified USGS 2014 probabilistic ground motion grid and Hazus will apply standard National Earthquake Hazard Reduction Program (NEHRP) soil amplification factors to the ground motions based on the user's soil map data.

15.1 Development of Probabilistic Seismic Hazard Data for Use in Hazus

The USGS provided the probabilistic seismic hazard data for the entire United States. A three-step process was used to convert the data into a Hazus compatible format.

Step 1: Compute the PGA, $SA_{0.3}$, and $SA_{1.0}$ at each grid point for the eight return periods.

The latest 2014 national seismic hazard model of the USGS was used (Petersen et al., 2014). The hazard dataset consists of a set of 19 (or 20) intensity probability pairs for each of the 611,309 grid points used to cover the contiguous United States. The hazard models for Alaska, Hawaii, and Puerto Rico are not of the same vintage, hence, Hazus utilizes data derived from the 2007 model for Alaska, the 1998 model for Hawaii, and the 2003 model for Puerto Rico.

For each grid point, a log-log interpolation of the data is used to calculate the ground motion values corresponding to each of the eight return periods (100, 250, 500, 750, 1,000, 1,500, 2,000, and

2,500 years). This represents an improvement over prior versions of the probabilistic data, which utilized linear interpolation; log-log interpolation provides a superior fit to the hazard.

Step 2: Modify the PGA, $SA_{0.3}$, and $SA_{1.0}$ at each grid point to represent site-soil conditions

The USGS hazard data were derived assuming a National Earthquake Hazard Reduction Program (NEHRP) soil class type B/C (medium rock/very dense soil). To account for the difference in soil class types specific to each grid cell, the topography-based Vs30 estimates available from the USGS website were used, along with the NEHRP site soil correction factors (FEMA, 2015) to derive the site soil corrected PGA, $SA_{0.3}$, and $SA_{1.0}$ at each grid point.

Step 3: Compute the PGA, $SA_{0.3}$, and $SA_{1.0}$ at each Census tract centroid for the eight return periods.

For estimating losses to the building inventory, Hazus uses the ground shaking values generalized to the Census tract; area-weighted ground motion values are applied to each Census tract.

15.2 The Hazus AAL Module

Hazus can be used to generate direct economic losses for the probabilistic ground motions associated with each of the eight return periods, which can then be used to estimate the Average Annual Loss (AAL).

Figure 15-1 illustrates schematically a Hazus example of eight loss estimates plotted against the exceedance probabilities for the ground motions used to calculate these losses. Hazus computes the AAL by estimating the area under the loss probability curve. This area represents an approximation to the AAL and is equivalent to taking the summation of the differential probabilities, multiplied by the average loss for the corresponding increment of probability. In effect, the area under the curve is being approximated by summing the area of horizontal rectangular slices.

The details of this calculation are illustrated in Table 15-1 (FEMA, 2017). Hazus computes losses for the eight probabilistic return periods as shown in the return period (RP) column. The annual probability of the occurrence of each event is 1/RP. The differential probabilities are obtained by subtracting the annual occurrence probabilities for adjacent events. Next, the average loss is computed by averaging the losses associated with various adjacent return periods as shown in the average losses column. Once average loss is computed, the average annualized loss is the summation of the product of the average loss and differential probability of experiencing this loss.

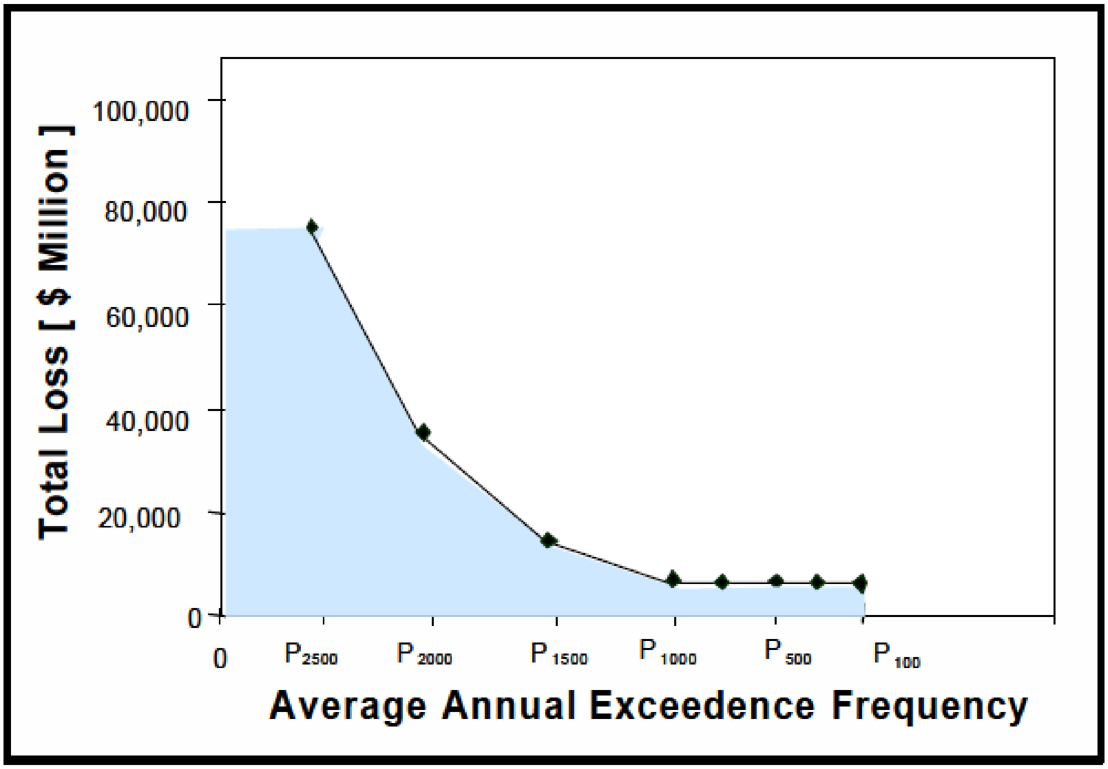


Figure 15-1 Average Annualized Earthquake Loss Computation Probabilistic Loss Curve

Table 15-1 Annualized Loss Calculations

Return Period	Annual Probability	Differential Probabilies		Annual Losses	Average Losses	Annualized Losses
		Formula	Values			
2500	0.00040	P2500	0.0004	L2500	L2500	P2500 * L2500
2000	0.00050	P2000 – P2500	0.0001	L2000	(L2000+L2500)/2	(P2000-P2500) * (L2000+L2500)/2
1500	0.00067	P1500 – P2000	0.00017	L1500	(L1500+L2000)/2	(P1500 – P2000) * (L1500+L2000)/2
1000	0.00100	P1000 – P1500	0.00033	L1000	(L1000+L1500)/2	(P1000 – P1500) * (L1000+L1500)/2
750	0.00133	P750 – P1000	0.00033	L750	(L750+L1000)/2	(P750 – P1000) * (L750+L1000)/2
500	0.002	P500 – P750	0.00067	L500	(L500+L750)/2	(P500 – P750) * (L500+L750)/2
250	0.004	P250 – P500	0.002	L250	(L250+L500)/2	(P250 – P500) * (L250+L500)/2
100	0.01	P100 – P250	0.006	L100	(L100+L250)/2	(P100 – P250) * (L100+L250)/2

** After FEMA, 2017*

The original choice for the number of return periods was important for evaluating average annual losses, so that a representative curve could be connected through the points and the area under the probabilistic loss curve would be a good approximation. The constraint on the upper bound of the number was computational efficiency vs. improved marginal accuracy. In order to determine the appropriate number of return periods, a sensitivity study was completed during the original Hazus development process that compared the stability of the AEL results to the number of return periods for 10 metropolitan regions using 5, 8, 12, 15, and 20 return periods. The difference in the AEL results using eight 8, 12, 15, and 20 return periods was negligible.

Section 16. References

Abrahamson, N. A., and W. J. Silva. 2008. Summary of the Abrahamson & Silva NGA Ground-Motion Relations. *Earthquake Spectra*, 24(1): 67-97.

Allen and Hoshall, Jack R. Benjamin and Associates, and Systan Inc. 1985*. An Assessment of Damage and Casualties for Six Cities in the Central United States Resulting from Earthquakes in the New Madrid Seismic Zone*. Prepared for FEMA.

Algermissen, S. T., M. Hopper, K. Campbell, W. A. Rinehart, D. Perkins, K. V. Steinbrugge, H. J. Lagorio, D. F. Moran, L. S. Cluff, H. J. Degenkolb, C. M. Duke, G. 0. Gates, D. W. Jacobson, R. A. Olson, and C. R. Allen. 1973. *A Study of Earthquake Losses in the Los Angeles, California Area*. Washington, D.C.: National Oceanic and Atmospheric Administration (NOAA).

Applied Technology Council. 1985. *Earthquake Damage Evaluation Data for California, ATC-13*. Redwood City: Applied Technology Council.

Applied Technology Council. 2010. *Here Today – Here Tomorrow: The Road to Earthquake Resilience in San Francisco, Potential Earthquake Impacts: Technical Documentation*. Redwood City, CA: Applied Technology Council Publication ATC 52-1A.

Aroni, S., and Durkin, M. E. 1985. Injuries and Occupant Behavior in Earthquakes. *Proc. Joint U.S. - Romanian Seminar on Earthquake & Energy,* Vol. 2 (September): 3-40.

Atkinson G.M., and D.M. Boore. 2002. Empirical Ground-motion Relationships for Subduction Zone Earthquake and their Application to Cascadia and Other Regions*. Bulletin of the Seismological Society of America***,** in review.

Atkinson, G.M., and D.M. Boore. 2006. Earthquake Ground-Motion Prediction Equations for Eastern North America. *Bulletin of the Seismological Society of America*, Vol. 96, no. 6: 2181-2205. doi: 10.1785/0120050245.

Bartlett, S.F., and T.L. Youd. 1992. Empirical Prediction of Lateral Spread Displacement. edited by*:* Hamada, M., and O'Rourke, T. D., *Proceedings from the Fourth Japan-U.S. Workshop on Earthquake Resistant Design of Lifeline Facilities and Countermeasures for Soil Liquefaction*, v I: 351 – 365.*,* Technical Report NCEER-92-0019.

Basoz, Nesrin, and John Mander. 1999. *Enhancement of the Highway Transportation Lifeline Module in Hazus*, prepared for the National Institute of Building Sciences (January).

Boore, D.M., and Atkinson M.A. 2008. Ground-motion prediction equations for the average horizontal component of PGA, PGV, and 5%-Damped PSA at spectral periods between 0.01s and 10.0s. *Earthquake Spectra*, 24(1):99-138.

Campbell, K.W., and Y. Bozorgnia. 2003. Updated Near-Source Ground-Motion (Attenuation) Relations for the Horizontal and Vertical Components of Peak Ground Acceleration and Acceleration Response Spectra*. Bulletin of the Seismological Society of America,* v. 93, no. 1 (February): 314-331.

Campbell, K. W. and Y. Bozorgnia. 2008. NGA ground motion model for the geometric mean horizontal component of PGA, PGV, PGD and 5% damped linear elastic response spectra for periods ranging from 0.01 to 10s*.. Earthquake Spectra*, 24(1): 139-171.

Cheu, D. H. 1994. Personal Communication – Comments on Casualty Issues, April.

Chiou, B. S. and Youngs R.R. 2008. An NGA model for the average horizontal component of peak ground motion and response spectra. *Earthquake Spectra*, 24(1): 173-215.

Chopra, Anil K., 1995. *Dynamics of Structures*. Prentice Hall, Engelwood Cliffs, New Jersey.

Coburn, A.W. and Spence, R.J. 1992. Factors Determining Human Casualty Levels in Earthquakes: Mortality Prediction in Building Collapse. *Proceedings of the 10WCEE*, Madrid : 5989 - 5994.

Comartin-Reis. 2001. *HAZUS99 SR-1 Validation Study*. Prepared for the National Institute of Buildings Sciences and the Federal Emregency Management Agency, Washington DC.

Composite Earthquake Catalog. 2002. *Advanced National Seismic System*, Berkeley: Northern California Earthquake Data Center.Czarnecki, Robert Martin. 1973. Earthquake Damage to Tall Buildings. *Structures Publication No. 359*, Dept. of Civil Engineering, M.I.T.

CUSEC Association of State Geologists. 2008. *Liquefaction Susceptibility Map*. https://cusec.org/earthquake-maps-data/

Dowding, C.H. and Rozen. 1978. A., Damage to Rock Tunnels from Earthquake Shaking. *Journal of the Geotechnical Engineering Division*, New York: American Society of Civil Engineers (February).

Durkin, M.E. 1992. Improving Earthquake Casualty and Loss Estimation. *Proc. 10 WCEE*, Madrid: 557 - 562.

Durkin, M. E. 1995. *Fatalities, Nonfatal Injuries, and Medical Aspects of the Northridge Earthquake,* The Northridge, California Earthquake of 17 January 1994, CDMG, Spec. Pub. 116, 247-254.

Durkin, M. and Murakami, H.1989. Casualties, Survival, and Entrapment in Heavily Damaged Buildings. *Proc. 9 WCEE*, Vol. VII, Kyoto:, 977 – 982.

Durkin, M. E. and Thiel, C. C. 1991. Integrating Earthquake Casualty and Loss Estimation. Sacramento: Proc. Of the Workshop on Modeling Earthquake Casualties for Planning and Response.

Earthquake Data Base. 2002. *National Earthquake Information Center*, Golden: United States Geological Survey.

EERI. 1986. *Report on the North Palm Springs, California earthquake*—July 8, 1986. Oakland, Earthquake Engineering Research Institute.

Egan, J.A., and D.A. Sangrey. 1978. Critical State Model for cyclic load pore pressure, Proceedings. *Earthquake Engineering and Soil Dynamics Conference and Exhibit*, Pasadena, (June): 19-21.

Federal Emergency Management Agency (FEMA). 1992. *FEMA 178 - NEHRP Handbook for the Seismic Evaluation of Existing Buildings,* Washington, D. C.: Developed by the Building Seismic Safety Council (BSSC) for the Federal Emergency Management Agency (FEMA).

Federal Emergency Management Agency (FEMA). 1992a. *A Benefit-Cost Model for the Seismic Rehabilitation of Buildings, Volume 1: A User's Manual*. Washington, D.C.: Federal Emergency Management Agency, FEMA Publication 227.

Federal Emergency Management Agency (FEMA). 1992b. *A Benefit-Cost Model for the Seismic Rehabilitation of Buildings, Volume 2: Supporting Documentation*. Washington, D.C.: Federal Emergency Management Agency, FEMA Publication 227.

Federal Emergency Management Agency (FEMA). 1994a. *Seismic Rehabilitation of Federal Buildings: A Benefit/Cost Model, Volume 1: A User's Manual*. Washington, D.C.: Federal Emergency Management Agency, FEMA Publication 255.

Federal Emergency Management Agency (FEMA). 1994b. *Seismic Rehabilitation of Federal Buildings: A Benefit/Cost Model, Volume 2: Supporting Documentation*. Washington, D.C.: Federal Emergency Management Agency, FEMA Publication 255.

Federal Emergency Management Agency (FEMA). 1995a. *NEHRP Recommended Provisions for Seismic Regulations for New Buildings*, Washington, D.C.: Part 1 - Provisions. FEMA 222A.

Federal Emergency Management Agency (FEMA). 1996a. *NEHRP Guidelines for the Seismic Rehabilitation of Buildings*. Washington, D.C.: FEMA 273.

Federal Emergency Management Agency (FEMA). 2000. *Recommended Seismic Evaluation and Upgrade Criteria for Existing Welded Steel Moment-Frame Buildings*. Washington D.C.; Federal Emergency Management Agency, FEMA Publication 351.

Federal Emergency Management Agency (FEMA). 2006. *Designing for Earthquakes: A Manual for Architects*. Washington, D.C.: Federal Emergency Management Agency, FEMA Publication 454.

Federal Emergency Management Agency (FEMA). 2015. *NEHRP Recommended Seismic Provisions for New Buildings and Other Structures Volume I: Part 1 Provisions, Part 2 Commentary,* FEMA P-1050-1/2015 Edition, Prepared for the Federal Emergency Management Agency of the U.S. Department of Homeland Security by the Building Seismic Safety Council of the National Institute of Building Sciences, Washington, D.C.

Federal Emergency Management Agency (FEMA). 2017. *Hazus Estimated Annualized Earthquake Losses for the United States*, Federal Emergency Management Agency Publication (April): P-366. https://www.fema.gov/media-library-data/1497362829336-7831a863fd9c5490379b28409d541efe/FEMAP-366_2017.pdf

Federal Emergency Management Agency (FEMA). 2019. *Hazus Earthquake Model, FEMA Standard Operating Procedure for Hazus Earthquake Data Preparation and Scenario Analysis.* Federal Emergency Management Agency (May).

Ferritto, J.M. 1982. *An Economic Analysis of Earthquake Design Levels*. Port, Hueneme: Naval Civil Engineering Laboratory, TN No. N-1640.

Ferritto, J.M. 1983. *An Economic Analysis of Earthquake Design Levels for New Concrete Construction*. Port Hueneme: Naval Civil Engineering Laboratory, TN No. N-1671.

Frankel, A., C. Mueller, T. Barnhard, D. Perkins, E. Leyendecker, N. Dickman, S. Hanson, and M. Hopper, 1996. *National seismic-hazard maps: documentation* June 1996, U.S. Geological Survey, Open-file Report: 96-532: 110 pp.

G&E Engineering Systems, Inc. (G&E), 1994a, *NIBS Earthquake Loss Estimation Methods, Technical Manual*, *Transportation Systems (Highway Systems),* May 1994.

G&E Engineering Systems, Inc. (G&E), 1994b, *NIBS Earthquake Loss Estimation Methods, Technical Manual, Transportation Systems (Railway, Light Rail, Bus, Port, Ferry and Airport Systems*), May 1994.

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

G&E Engineering Systems, Inc. (G&E), 1994d, *NIBS Earthquake Loss Estimation Methods*, *Technical Manual, Fuel Line Systems, Communication Systems, Waste Water Systems*, May 1994.

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

Golden Gate Divisional Multidisciplinary Accident Investigation Team (MAIT). 1990a. *I-80 San Francisco-Oakland Bay Bridge Structure Collapse Report*, Sacramento: California Highway Patrol.

Golden Gate Divisional Multidisciplinary Accident Investigation Team (MAIT). 1990b. *I-880 Nimitz Freeway (Cypress viaduct) Structure Collapse Report*, Sacramento: California Highway Patrol.

Goodman, R.E., and H.B. Seed. 1966. Earthquake-Induced Displacements in Sand Embankments. *Journal of the Soil Mechanics and Foundations Division, Proceedings of the American Society of Civil Engineers*, vol. 92, no. SM2: 125-146.

Grant, W.P., Perkins, W.J. and T.L. Youd. 1991. Evaluation of Liquefaction Potential in Seattle, Washington,- *USGS Professional Paper 91-0441T*, United States Geological Survey.

Hamada, M. 1975. *Architectural Fire Resistant Themes,* No 21., Kenchikugaku Taikei, Shokokusha, Tokyo.

Harrald, J. R., Al-Hajj, S., Fouladi, B., and Jeong, D. 1994. *Estimating the Demand for Sheltering in Future Earthquakes*. IEEE Transactions in Engineering Management, (Publication currently pending).

Harrald, J. R., Fouladi, B., and Al-Hajj, S. F. 1992. *Estimates of Demand for Mass Care Services in Future Earthquakes Affecting the San Francisco Bay Region*. Prepared by George Washington University for the American Red Cross Northern California Earthquake Relief and Preparedness Project (NCERPP), 41 pp. plus appendices.

Hasselman, T.K., Ronald T. Eguchi, and John H. Wiggins. 1980. *Assessment of Damageability for Existing Buildings in a Natural Hazards Environment*. Volume I: Methodology. Redondo Beach.

Honegger, D.G. and Eguchi, R.T. 1992. *Determination of Relative Vulnerabilities to Seismic Damage for San Diego County Water Authority (SDCWA) Water Transmission Pipelines*, (October) .

Howe, C.W., and H.C. Cochrane. 1993. *Guidelines for the Uniform Identification, Definition, and Measurement of Economic Damages from Natural Hazard Events*, Institute of Behavioral Science: University of Colorado.

International Conference of Building Officials, *Uniform Fire Code*, 1997.

Isoyama, R. and Katayama, T.1998. Reliability Evaluation of Water Supply Systems During Earthquakes, February 1992.

Jones, N. P., Smith, G. S. and R. M. Wagner. 1994. Morbidity and Mortality in the Loma Prieta Earthquake: A Review of Recent Findings*. Research Accomplishments 1986-1994*, NCEER: 95-106.

Joyner, W.B., and D.M. Boore. 1988. Measurement, Characterization, and Prediction of Strong Ground Motion. *Proceedings of Earthquake Engineering & Soil Dynamics II*, 43- 102. Park

City, Utah, 27 June 1988. New York: Geotechnical Division of the American Society of Civil Engineers.

Keefer, D. K.1984. Landslides Caused by Earthquakes.", *Geological Society of America Bulle*tin, vol. 95: 406-421.

Kennedy, R. P., C. A. Cornell, R. L. Campbell, S. Kaplan, and H. F. Perla. 1980. Probabilistic Seismic Safety of an Existing Nuclear Power Plant*. Nuclear Engineering and Design*, 59(2): 315- 38.

Kircher, Charles A. 2002. *Development of New Fragility Function Betas for Use with Shake Maps*. prepared for the National Institute of Building Sciences and the Federal Emergency Management Agency.

Klein, F., Frankel, A.D., Mueller, C.S., Wesson, R.L., and P. Okubo. 1998*. "*Documentation for Draft Seismic-Hazard Maps for the State of Hawaii", *United States Geological Survey*.

Klein, F., Frankel, A.D., Mueller, C.S., Wesson, R.L., and P. Okubo. 2001. "Seismic Hazard in Hawaii: High Rate of Large Earthquakes and Probabilistic Ground-Motion Maps.", *Bulletin of the Seismological Society of America*, Vol. 91, No. 3: 479-498.

Knudsen, K.L, J.M. Sowers, R.C. Witter, C.M. Wentworth, E.J. Helley, R.S. Nicholson and H.M. Wright. 2000. *Preliminary Maps of Quaternary Deposits and Liquefaction Susceptibility, Nine-County San Francisco Bay Region, California: a Digital Database*, United States Geological Survey Open-File Report 2000-444. https://doi.org/10.3133/ofr00444

Kustu, O., D. D. Miller, and S. T. Brokken. 1982. *Development of Damage Functions for High-Rise Building Components*. San Francisco, Prepared by URS/John A. Blume & Associates for the U.S. Department of Energy

Lee, K. L., and Albaisa, A.. 1974. Earthquake Induced Settlement in Saturated Sands., *Journal of the Soil Mechanics and Foundation Division*, ASCE 100(GTA): 387-406.

Liao, S.S., Veneziano, D., and R.V. Whitman. 1988. Regression Models for Evaluating Liquefaction Probability, *Journal of Geotechnical Engineering*, vol. 114, No. 4 (April).

Mahaney, James A., Terrence F. Paret, Bryan E. Kehoe, and Sigmund A. Freeman. 1993. *The Capacity Spectrum Method for Evaluating Structural Response during the Loma Prieta Earthquake*. Proceedings of the 1993 United States National Earthquake Conference, Memphis,, Vol. 2, 501-510.

Makdisi, F. I. and H.B. Seed. 1978. Simplified Procedure for Estimating Dam and Embankment Earthquake-Induced Deformations*. Journal of the Geotechnical Engineering Division, American Society of Civil Engineers*, vol. 104, No. GT7 (July): 849-867.

Martin G.R., Finn, W.D., and H.B. Seed. 1975. Fundamentals of Liquefaction Under Cyclic Loading*. Journal of the Geotechnical Engineering Division*, ASCE 104(GT5): 423-438.

Mohammadi, J., Alyasin, S., and Bak, D. N. 1992. *Investigation of Cause and Effects of Fires Following the Loma Prieta Earthquake,* Report IIT-CE-92-01, Chicago, Illinois Institute of Technology.

Mueller, C.S., A.D. Frankel, M.D. Petersen and E.V. Leyendecker. 2010. New Seismic Hazard Maps for Puerto Rico and the U.S. Virgin Islands. *Earthquake Spectra*, Vol. 26, No.1: 169 – 185.

Munson, C.G., and C.H. Thurber. 1997. Analysis of the Attenuation of Strong Ground Motion on the Island of Hawaii. *Bulletin of the Seismological Society of America*, vol. 87, No. 4 (August): 945-960.

Murakami H. O. 1992. *A Simulation Model to Estimate Human Loss for Occupants of Collapsed Buildings in an Earthquake,* Proceedings of the 10. WCEE, Madrid: 5969 - 5974.

National Research Council. 1985. *Liquefaction of Soils During Earthquakes,* Committee on Earthquake Engineering, Commission on Engineering and Technical Systems, Washington, D.C.: National Academy Press.

National Bridge Inventory (NBI), 2018 https://catalog.data.gov/dataset/national-bridge-inventory-system-nbi-1992-b9105

Newmark, N.M. 1965. Effects of Earthquakes on Dams and Embankments.*Geotechnique*, vol. 15, no. 2: 139-160.

Newmark, N.M. and W.J. Hall. 1982. *Earthquake Spectra and Design*. Earthquake Engineering Research Institute Monograph.

Noji, E.K. 1990. *Epidemic Studies from the 1988 Armenia Earthquake: Implications for Casualty Modeling*, Workshop on Modeling Earthquake Casualties for Planning and Response, VSP Associates, Pacific Grove: Asilomar Conference Center.

OAK Engineering Inc. (OAK). 1994. *Development of Damage Functions for Buildings*.

O'Rourke, M.J and Ayala, G., 1993. *Pipeline Damage due to Wave Propagation*, *Journal of Geotechnical Engineering*, ASCE, Vol 119, No.9, Sept. 1993.

Owen, G.N. and Scholl, R.E. 1981. *Earthquake Engineering Analysis of a Large Underground Structures*, Federal Highway Administration and National Science Foundation, FHWA/RD-80/195, (January).

Peek-Asa, C., Kraus, J.F., Bourque, L. B., Vimalachandra, D., Yu, J. and J. Abrams. 1998. Fatal and Hospitalized Injuries Resulting From the 1994 Northridge Earthquake., *International Journal of Epidemiology*, V27, 459-465.

Perkins, J. B. 1992. *Estimates of Uninhabitable Dwelling Units in Future Earthquakes Affecting the San Francisco Bay Region*. Oakland: ABAG: 89 .

Perkins, J.B., Harrald, J.R., and others, unpublished. *Preliminary Results of an NSF-Sponsored Project on Modeling Housing Damage in Earthquakes and Resulting Mass-Care Needs*, NSF Grant BCS-9441459.

Petersen, Mark D., Frankel, Arthur D., Harmsen, Stephen C., Mueller, Charles S., Haller, Kathleen M., Wheeler, Russell L., Wesson, Robert L., Zeng, Yuehua, Boyd, Oliver S., Perkins, David M., Luco, Nicolas, Field, Edward H., Wills, Chris J., and Rukstales, KennethS. 2008. “Documentation for the 2008 Update of the United States National Seismic Hazard Maps, *U.S. Geological Survey Open-File Report 2008–1128*: 61

Petersen, M.D., Moschetti, M.P., Powers, P.M., Mueller, C.S., Haller, K.M., Frankel, A.D., Zeng, Yuehua, Rezaeian, Sanaz, Harmsen, S.C., Boyd, O.S., Field, Ned, Chen, Rui, Rukstales, K.S., Luco, Nico, Wheeler, R.L., Williams, R.A., and Olsen, A.H. 2014. Documentation for the 2014 update of the United States national seismic hazard maps. *U.S. Geological Survey Open-File Report 2014–1091*: 243 . https://dx.doi.org/10.3133/ofr20141091.

Petersen, Mark, Mueller, Charles, Moschetti, Morgan, Hoover, Susan, Shumway, Allison, Mcnamara, Daniel, Williams, Robert, Llenos, Andrea. Ellsworth, William, Michael, Andrew, Rubinstein, Justin, Mcgarr, A. and Rukstales, Kenneth. 2017. One-Year Seismic-Hazard Forecast for the Central and Eastern United States from Induced and Natural Earthquakes. *Seismological Research Letters,* 88: 772-783. 10.1785/0220170005.

Petersen, Mark, Mueller, Charles. Moschetti, Morgan, Hoover, Susan, Rukstales, Kenneth, Mcnamara, Daniel, Williams, Robert, Shumway, Allison, Powers, Peter, Earle, Paul, Llenos, Andrea, Michael, Andrew, Rubinstein, Justin, Norbeck, Jack and Cochran, Elizabeth. 2018. 2018 One-Year Seismic Hazard Forecast for the Central and Eastern United States from Induced and Natural Earthquakes. *Seismological Research Letters,* 89. 10.1785/0220180005.

Petersen, Mark D., Allison M. Shumway, Peter M. Powers, Charles S. Mueller, Morgan P. Moschetti, Arthur D. Frankel, Sanaz Rezaeian, Daniel E. McNamara, Nico Luco, Oliver S. Boyd, Kenneth S. Rukstales, Kishor S. Jaiswal, Eric M. Thompson, Susan M. Hoover, Brandon S. Clayton, Edward H. Field and Yuehua Zeng. 2020. 2018 update of the U.S. National Seismic Hazard Model: Overview of model, changes, and implications. *Earthquake Spectra*. https://doi.org/10.1177%2F8755293019878199.

Porter, K.A., J.L. Beck, H.A. Seligson, C.R. Scawthorn, L.T. Tobin, R. Young, and T. Boyd. 2002. *Improving Loss Estimation for Woodframe Buildings*. CUREE-Caltech Woodframe Project, CUREE Publication No. W-18.

Power, M. S., A.W. Dawson, D.W. Streiff, R.G. Perman, and S. C. Haley. 1982. *Evaluation of Liquefaction Susceptibility in the San Diego, California Urban Area*. Proceedings 3rd International Conference on Microzonation II: 957-968.

Power, M. S., R. G. Perman, J. R. Wesling, R. R. Youngs, M. K. Shimamoto. 1991. *Assessment of Liquefaction Potential in the San Jose, California Urban Area*. Stanford: Proceedings 4th International Conference on Microzonation, II:,677-684.

Power, M. S., Taylor, C. L., and Perman, R. C. 1994. *Evaluation of Regional Landsliding Hazard Potential for Utility District - Eastern San Francisco Bay Area*. Chicago: Proceedings of the U.S. Fifth National Conference on Earthquake Engineering (July).

Power, M.S., Wesling, J.R., Perman, R.C., Youngs, R.R., and DiSilvestro, L.A. 1992. Evaluation of liquefaction potential in San José, California. *U.S. Geological Survey Final Technical Report*, Award no. 14-08-0001-G1359, (May):, 65

Rogers, A. M., S. T. Algermissen, W. W. Hays, D. M. Perkins, D. 0. Van Strien, H. C. Hughes, R. C. Hughes, H. J. Lagorio, and K. V. Steinbrugge. 1976. A Study of Earthquake Losses in the Salt Lake City, Utah Area. *USGS Open-File Report,*. Washington, D.C.: United States Geological Survey: 76-89.

Sadigh, K., Chang C. Y., Egan, J., Makdisi, F. and R. Youngs. 1997. Attenuation Relationships for Shallow Crustal Earthquakes based on California Strong Motion Data. *Seismological Research Letters*, v. 68, no. 1: 180-189.

Sadigh, K., Egan, J. A., and Youngs, R. R. 1986. Specification of Ground Motion for Seismic Design of Long Period Structures. *Earthquake Notes*, vol. 57, no. 1: 13, relationships are tabulated in Joyner and Boore (1988) and Youngs and others (1987).

Scawthorn, C., J. Donelan. 1984. *Fire-Related Aspects of the Coalinga Earthquake.* In Coalinga California Earthquake of May 2 1983: Reconnaissance Report. Report 84-03. Berkeley, CA: EERI.

Scawthorn, C., G. Bureau, C. Jessup, R. Delgado. 1985. Fire-Related Aspects of 24 April 1984 Morgan Hill Earthquake. *Spectra 1*, no. 3, (May): 675-*685*.

Scawthorn, C. 1987. *Fire following earthquake: estimates of the conflagration risk to insured property in greater Los Angeles and San Francisco*. Oak Brook*:* All-Industry Research Advisory Council.

Scawthorn, C., K. A. Porter, et al. 1991. *Performance of Emergency Response Services After the Earthquake. Chapter in The Loma Prieta California Earthquake of October 17 1989 - Marina District.* USGS Prof. Paper 1551-F, edited by O'Rourke, T.D. and Holzer, T.,. Washington GPO.

Scawthorn, C. 1996. *Fire Following the Northridge and Kobe Earthquakes*, U.S./Japan Government Cooperative Program on Natural Resources (UJNR). Fire Research and Safety. 13th Joint Panel Meeting. Volume 2 , edited by Beall, K. A.,:325-335, 1997, Gaithersburg: National Inst. Of Standards and Technology.

Scawthorn, C., Cowell, A. D., and Borden, F. 1997. *Fire-Related Aspects of the Northridge Earthquake.* Report prepared for the Building and Fire Research Laboratory, Gaithersburg: National Institute of Standards and Technology, NIST-GCR-98-743.

Seed, H. B., and Idriss, I. M. 1982. *Ground Motions and Soil Liquefaction During Earthquakes*, Earthquake Engineering Research Institute, Oakland: Monograph Series, 13.

Seed, H. B., Tokimatsu, K., Harder, L. F. and Chung, R. M. 1985. "Influence of SPT Procedures in Soil Liquefaction Resistance Evaluations. *Journal of Geotechnical Engineering, American Society of Civil Engineers*, vol. 111, no. 12, 1425-1445.

Seed, R. B., and Harder, L. F. 1990. *SPT-Based Analysis of Cyclic Pore Pressure Generation and Undrained Residual Strength*, Proceedings of the H. B. Seed Memorial Symposium, vol. 2: 351-376.

Shiono, K., Krimgold, F. and Ohta, Y. 1991a. *A Method for the Estimation of Earthquake Fatalities and its Applicability to the Global Macro-Zonation of Human Casualty Risk,* Proc. Fourth International Conference on Seismic Zonation, Stanford, Vol. III: 277 - 284.

Shiono, K., Krimgold, F., Ohta, Y. 1991b. Post-Event Rapid Estimation of Earthquake Fatalities for the Management of Rescue Activity*. Comprehensive Urban Studies*, No. 44: 61 - 105.

Silva, W., Gregor, N., and Darragh, R. 2002. *Development of hard rock attenuation relations for central and eastern North America*, internal report from Pacific Engineering, (November).

Somerville, P., Collins, N., Abrahamson, R., and C. Saikia. 2001. *Ground-motion Attenuation Relationships for the Central and Eastern United States*, final report to the U.S. Geological Survey.

Somerville, P., N.F. Collins, N.A. Abrahamson, R.W. Graves and C.K. Saikia, 2002, "Earthquake Source Scaling and Strong Ground Motion Attenuation Relations in Eastern North America", American Geophysical Union, Fall Meeting, December 2002, abstract id. S21B-0994.

SPA Risk. 2009. *Enhancements in Hazus-MH Fire Following Earthquake, Task 3: Updated Ignition Equation,* SPA Project No. 10010-01-07-01, SPA Risk LLC, Berkeley CA. Principal Investigator C. Scawthorn. San Francisco: Prepared for PBS&J and the National Institute of Building Sciences.

State of California, Division of the State Architect (DSA). 1996. *Earthquake Hazard Mitigation Technology Application Guidelines*. Sacramento.

State of California, Seismic Safety Commission (SSC). 1996. *Seismic Evaluation and Retrofit of Concrete Buildings*. Report No. SSC 96-01, Sacramento.

State of California, Seismic Safety Commission (SSC). 1995. *Turning Loss to Gain*. Report No. SSC 95-01, Sacramento.

Stewart, Jonathan P. and Emel Seyhan. 2013. *Semi-Empirical Nonlinear Site Amplification and its Application in NEHRP Site Factors*, Pacific Earthquake Engineering Research Center Report, PEER 2013/13. https://peer.berkeley.edu/sites/default/files/webpeer-2013-13-jonathan_p._stewart_and_emel_seyhan.pdf.

Stojanovski, P., Dong, W.1994 *Simulation Model for Earthquake Casualty Estimation,* Proc. Fifth U.S. National Conference on Earthquake Engineering, Paper No. 00592, Chicago: (July): 10-14.

Tang, A. and Wong, F.1994, *Observation on Telecommunications Lifeline Performance in the Northridge Earthquake of January 17, 199*4, Magnitude 6.6.

Tavakoli, B., and Pezeshk, S. 2005. Empirical-stochastic ground-motion prediction for eastern North America*. Bulletin of the Seismological Society of America*, v. 95, 2283–2296.

Tinsley, J. C., T. L. Youd, D. M. Perkins, and A. T. F. Chen. 1985. *Evaluating Liquefaction Potential, Evaluating Earthquake Hazards in the Los Angeles Region*, USGS Professional Paper 1360:263-316.

Tokimatsu, A. M., and Seed, H. B. 1987. Evaluation of Settlements in Sands Due to Earthquake Shaking. *Journal of the Geotechnical Division, American Society of Civil Engineers,* vol. 113, no. 8: 681-878.

Toro, G. R., Abrahamson, N. A. and Schneider, J. F. 1997. Engineering Model of Strong Ground Motions from Earthquakes in the Central and Eastern United States. *Seismological Research Letters*, v. 68: 41-57.

Updike, R. G., Egan, J. A., Moriwaki, Y., Idriss, I. M., and Moses, T. L. 1988. A Model for Earthquake-Induced Translatory Landslides in Quaternary Sediments., *Geological Society of America Bulletin*, vol. 100, (May):783-792.

Wagner, R. M. 1996. *A Case-Control Study of Risk Factors for Physical Injury During the Mainshock of the 1989 Loma Prieta earthquake in the County of Santa Cruz, California*, Ph.D. Dissertation, Johns Hopkins University.

Wells, D. L., and Coppersmith, K. J. 1994. New Empirical Relationships Among Magnitude, Rupture Length, Rupture Width, and Surface Displacement*., Bulletin of the Seismological Society of America*, v 84: 974-1002.

Wesson, Robert L., Boyd, Oliver S., Mueller, Charles S., Bufe, Charles G., Frankel, Arthur D., Petersen, Mark D. 2007. *Revision of time-Independent probabilistic seismic hazard maps for Alaska:* U.S. Geological Survey Open-File Report 2007-1043.

Whitman, Robert V., Tarek S. Aziz and Earl H. Wong. 1977. *Preliminary Correlations Between Earthquake Damage and Strong Ground Motion*. Boston:Structures Publication No. 564, Dept. of Civil Engineering, M.I.T.

Wieczorek, G. F., Wilson, R. C. and Harp, E. L. 1985. *Map of Slope Stability During Earthquakes in San Mateo County, California*, U.S. Geological Survey Miscellaneous Investigations Map I-1257-E, scale 1:62,500.

Wiggins, J. H. 1988. *Fire Ignitions from the Whittier Narrows Earthquake of October 1, 1987*, Crisis Management Corp.

Wilson, R. C., and Keefer D. K. 1985. *Predicting Areal Limits of Earthquake Induced Landsliding, Evaluating Earthquake Hazards in the Los Angeles Region,* U.S. Geological Survey Professional Paper, edited by Ziony, J. I.: 317-493.

Witter, R.C., K.L. Knudsen, J.M Sowers, C.M. Wentworth, R.D Koehler, C.E Randolph, S.K. Brooks and K.D Gans. 2006. *Maps of Quaternary Deposits and Liquefaction Susceptibility in the Central San Francisco Bay Region, California*. United States Geological Survey Open-File Report 2006-1037. https://doi.org/10.3133/ofr20061037

Wong, Earl Hom. 1975. C*orrelations Between Earthquake Damage and Strong Ground Motion*. Boston: Dept. of Civil Engineering, M.I.T.

Youd, T. L., and Hoose, S. N. 1978. Historic Ground Failures in Northern California Triggered by Earthquakes*. U.S. Geological Survey Professional Paper 993*: 177.

Youd, T. L., and Perkins, D. M. 1978. Mapping of Liquefaction Induced Ground Failure Potential*., Journal of the Geotechnical Engineering* Division, American Society of Civil Engineers, vol. 104, no. 4: 433-446.

Youd, T. L., and Perkins, D. M. 1987. Mapping of Liquefaction Severity Index*., Journal of the Geotechnical Engineering Division, American Society of Civil Engineers*, vol. 118, no. 11: 1374-1392.

Youngs R. R., Chiou, S. J., Silva W. L., and Humphrey J. R. 1997. Strong Ground Motion Attenuation Relationships for Subduction Zone Earthquakes., *Seismological Research Letters,* (January/February).

Zhao J.X., Zhang, J., Asano, A., Ohno, Y., Oouchi, T., Takahashi, T., Ogawa, H., Irikura, K., Thio, H., Somerville, P., Fukushima, Y., and Fukushima, Y. 2006. Attenuation relations of strong ground motion in Japan using site classification based on predominant period., *Bulletin of the Seismological Society of America,* v. 96: 898–913.

Appendix A: Subcomponent Damage Functions for Transportation Systems

Appendix A1 Subcomponent Damage Functions for Highway Tunnels

Any given subcomponent in the lifeline methodology can experience all five damage states; however, the only damage states listed in the appendices of Sections 7 and 8 are the ones used in the fault tree logic of the damage state of interest of the component. All data in this sub-appendix is sourced from G&E, 1994a.

Table A1-1 Subcomponent Peak Ground Acceleration Fragility Functions for Rock Tunnels

Subcomponent	Damage State	Median (g)	β
Liner	Slight	0.6	0.4
	Moderate	0.8	0.6

Table A1-2 Subcomponent Permanent Ground Deformation Fragility Functions for Rock Tunnels

Subcomponent	Damage State	Median (in)	β
Liner	Slight	6	0.7
	Extensive	12	0.5
	Complete	60	0.5
Portal	Slight	6	0.7
	Extensive	12	0.5
	Complete	60	0.5

Table A1-3 Subcomponent Peak Ground Acceleration Fragility Functions for Cut & Cover Tunnels

Subcomponent	Damage State	Median (g)	β
Liner	Slight	0.5	0.4
	Moderate	0.7	0.6

Table A1-4 Subcomponent Peak Ground Deformation Fragility Functions for Cut & Cover Tunnels

Subcomponent	Damage State	Median (in)	β
Liner	Slight	6	0.7
	Moderate	12	0.5
	Extensive/Complete	60	0.5
Portal	Slight	6	0.7
	Moderate	12	0.5
	Extensive/Complete	60	0.5

Appendix A2 Subcomponent Damage Functions for Rail Facilities

All data in this sub-appendix is sourced from G&E, 1994b.

Table A2-1 Subcomponent Peak Ground Acceleration Fragility Functions for Fuel Facilities with Anchored Components

Subcomponents	Damage State	Median (g)	β
Electric Power (Backup)	Slight	0.80	0.60
	Moderate	1.00	0.80
Electric Power (Off-Site)	Slight	0.15	0.60
	Moderate	0.25	0.50
Tank	Slight	0.30	0.60
	Moderate	0.70	0.60
	Extensive	1.25	0.65
	Complete	1.60	0.60
Pump Building	Slight	0.15	0.80
	Moderate	0.40	0.80
	Extensive	0.80	0.80
	Complete	1.50	0.80
Horizontal Pump	Extensive	1.60	0.60
Equipment	Moderate	1.00	0.60

Table A2-2 Subcomponent Peak Ground Acceleration Fragility Functions for Fuel Facilities with Unanchored Components

Subcomponents	Damage State	Median (g)	β
Electric Power (Backup)	Slight	0.20	0.60
	Moderate	0.40	0.80
Electric Power (Off-Site)	Slight	0.15	0.60
	Moderate	0.25	0.50
Tank	Slight	0.15	0.70
	Moderate	0.35	0.75
	Extensive	0.68	0.75
	Complete	0.95	0.70
Pump Building	Slight	0.15	0.80
	Moderate	0.40	0.80
	Extensive	0.80	0.80
	Complete	1.50	0.80
Horizontal Pump	Extensive	1.60	0.60
Equipment	Moderate	0.60	0.60

Table A2-3 Subcomponent Peak Ground Acceleration Fragility Functions for Dispatch Facilities with Anchored Components

Subcomponents	Damage State	Median (g)	β
Electric Power (Backup)	Slight	0.80	0.60
	Moderate	1.00	0.80
Electric Power (Off-Site)	Slight	0.15	0.60
	Moderate	0.25	0.50
Building	Slight	0.15	0.80
	Moderate	0.40	0.80
	Extensive	0.80	0.80
	Complete	1.50	0.80
Equipment	Moderate	1.00	0.60

Table A2-4 Subcomponent Peak Ground Acceleration Fragility Functions for Dispatch Facilities with Unanchored Components

Subcomponents	Damage State	Median (g)	β
Electric Power (Backup)	Slight	0.20	0.60
	Moderate	0.40	0.80
Electric Power (Off-Site)	Slight	0.15	0.60
	Moderate	0.25	0.50
Building	Slight	0.15	0.80
	Moderate	0.40	0.80
	Extensive	0.80	0.80
	Complete	1.50	0.80
Equipment	Moderate	0.60	0.60

Appendix A3 Subcomponent Damage Functions for Light Rail Facilities

All data in this sub-appendix is sourced from G&E, 1994b.

Table A3-1 Subcomponent Peak Ground Acceleration Fragility Functions for DC Power Substation with Anchored Components

Subcomponent	Damage State	Median (g)	β
Building	Slight	0.15	0.80
	Moderate	0.40	0.80
	Extensive	0.80	0.80
	Complete	1.50	0.80
Equipment	Moderate	1.00	0.60
Off-Site Power	Slight	0.15	0.60
	Moderate	0.25	0.50

Table A3-2 Subcomponent Peak Ground Acceleration Fragility Functions for DC Power Substation with Anchored Components

Subcomponent	Damage State	Median (g)	β
Building	Slight	0.15	0.80
	Moderate	0.40	0.80
	Extensive	0.80	0.80
	Complete	1.50	0.80
Equipment	Moderate	0.60	0.60
Off-Site Power	Slight	0.15	0.6
	Moderate	0.25	0.5

Appendix A4 Subcomponent Damage Functions for Waterfront Structures

All data in this sub-appendix is sourced from G&E, 1994b.

Table A4-1 Subcomponent Permanent Ground Deformation Fragility Functions for Waterfront Structures

Subcomponent	Damage State	Median (in)	β
Wharf	Slight	8	0.6
Piers	Slight	8	0.6
	Moderate	16	0.6
	Extensive	24	0.6
	Complete	60	0.6
Seawalls	Slight	8	0.6
	Moderate	16	0.6
	Extensive	24	0.6
	Complete	60	0.6

Appendix B: Subcomponent Damage Functions for Utility Systems

Appendix B1 Subcomponent Damage Functions for Potable Water Systems

All data in this sub-appendix is sourced from G&E, 1994c.

Table B1-1 Subcomponent Peak Ground Acceleration Fragility Functions for Potable Water Pumping Plants with Anchored Components

Subcomponent	Damage State	Median (g)	β
Electric Power (Backup)	Slight	0.80	0.60
	Moderate	1.00	0.80
Loss of commercial Power	Slight	0.15	0.40
	Moderate	0.30	0.40
Vertical/ Horizontal Pump[1]	Extensive	1.25/1.60	0.60
Building	Slight	0.15	0.80
	Moderate	0.40	0.80
	Extensive	0.80	0.80
	Complete	1.50	0.80
Equipment	Moderate	1.00	0.60

[1] Difference in median values has little effect on the fault tree analysis

Table B1-2 Subcomponent Peak Ground Acceleration Fragility Functions for Potable Water Pumping Plants with Unanchored Components

Subcomponent	Damage State	Median (g)	β
Electric Power (Backup)	Slight	0.20	0.60
	Moderate	0.40	0.80
Loss of commercial Power	Slight	0.15	0.40
	Moderate	0.30	0.40
Vertical/ Horizontal Pump[1]	Extensive	1.25/1.60	0.60
Building	Slight	0.15	0.80
	Moderate	0.40	0.80
	Extensive	0.80	0.80
	Complete	1.50	0.80
Equipment	Moderate	0.60	0.60

[1] Difference in median values has little effect on the fault tree analysis

Table B1-3 Subcomponent Peak Ground Acceleration Fragility Functions for Wells with Anchored Components

Subcomponent	Damage State	Median (g)	β
Electric Power (Backup)	Slight	0.80	0.60
	Moderate	1.00	0.80
Loss of commercial Power	Slight	0.15	0.40
	Moderate	0.30	0.40
Well Pump	Extensive	1.00	0.60
Building	Slight	0.15	0.80
	Moderate	0.40	0.80
	Extensive	0.80	0.80
	Complete	1.50	0.80
Electric Equipment	Moderate	1.00	0.60

Table B1-4 Subcomponent Peak Ground Acceleration Fragility Functions for Wells with Unanchored Components

Subcomponent	Damage State	Median (g)	β
Electric Power (Backup)	Slight	0.20	0.60
	Moderate	0.40	0.80
Loss of commercial Power	Slight	0.15	0.40
	Moderate	0.30	0.40
Well Pump	Extensive	1.00	0.60
Building	Slight	0.15	0.80
	Moderate	0.40	0.80
	Extensive	0.80	0.80
	Complete	1.50	0.80
Electric Equipment	Moderate	0.60	0.60

Table B1-5 Subcomponent Peak Ground Acceleration Fragility Functions for Sedimentation/Flocculation System

Subcomponent	Damage State	Median (g)	β
Basins	Slight	0.40	0.60
Baffles	Slight	0.70	0.60
Paddles	Moderate	0.80	0.60
Scrapers	Moderate	0.90	0.60

Table B1-6 Subcomponent Peak Ground Acceleration Fragility Functions for Water Treatment Plants with Anchored Components

Subcomponent	Damage State	Median (g)	β
Electric Power (Backup)	Slight	0.80	0.60
	Moderate	1.00	0.80
Loss of commercial Power	Slight	0.15	0.40
	Moderate	0.30	0.40
Chlorination Equipment	Slight	0.65	0.60
	Moderate	1.00	0.70
Sediment Flocculation	Slight	0.36	0.50
	Moderate	0.60	0.50
Chemical Tanks	Slight	0.40	0.70
	Moderate	0.65	0.70
Electric Equipment	Moderate	1.00	0.60
Elevated Pipe	Extensive	0.53	0.60
	Complete	1.00	0.60
Filter Gallery	Complete	2.00	1.00

Table B1-7 Subcomponent Peak Ground Acceleration Fragility Functions for Water Treatment Plants with Unanchored Components

Subcomponent	Damage State	Median (g)	β
Electric Power (Backup)	Slight	0.20	0.60
	Moderate	0.40	0.80
Loss of commercial Power	Slight	0.15	0.40
	Moderate	0.30	0.40
Chlorination Equipment	Slight	0.35	0.60
	Moderate	0.70	0.70
Sediment Flocculation	Slight	0.36	0.50
	Moderate	0.60	0.50
Chemical Tanks	Slight	0.25	0.60
	Moderate	0.40	0.60
Electric Equipment	Moderate	0.60	0.60
Elevated Pipe	Extensive	0.53	0.60
	Complete	1.00	0.60
Filter Gallery	Complete	2.00	1.00

Appendix B2 Subcomponent Damage Functions for Wastewater Systems

All data in this sub-appendix is sourced from G&E, 1994d.

Table B2-1 Subcomponent Peak Ground Acceleration Fragility Functions for Wastewater Treatment Plants with Anchored Components

Subcomponent	Damage State	Median (g)	β
Electric Power (Backup)	Slight	0.80	0.60
	Moderate	0.30	0.80
Loss of commercial Power	Slight	0.15	0.40
	Moderate	0.30	0.40
Chlorination Equipment	Slight	0.65	0.60
	Moderate	0.65	0.70
Sediment Flocculation	Slight	0.36	0.50
	Moderate	0.60	0.50
	Extensive	1.20	0.60
Chemical Tanks	Slight	0.40	0.60
	Moderate	0.65	0.60
Electrical/ Mechanical Equipment	Moderate	0.60	0.60
Elevated Pipe	Extensive	0.53	0.60
	Complete	1.00	0.60
Buildings	Complete	1.50	0.80

Table 8B-2 Subcomponent Peak Ground Acceleration Fragility Functions for Wastewater Treatment Plants with Unanchored Components

Subcomponent	Damage State	Median (g)	β
Electric Power (Backup)	Slight	0.20	0.60
	Moderate	0.40	0.80
Loss of commercial Power	Slight	0.15	0.40
	Moderate	0.30	0.40
Chlorination Equipment	Slight	0.35	0.60
	Moderate	0.70	0.70
Sediment Flocculation	Slight	0.36	0.50
	Moderate	0.60	0.50
	Extensive	1.20	0.60
Chemical Tanks	Slight	0.25	0.60
	Moderate	0.40	0.60
Electrical/ Mechanical Equipment	Moderate	0.60	0.60
Elevated Pipe	Extensive	0.53	0.60
	Complete	1.00	0.60
Buildings	Complete	1.50	0.80

Appendix B3 Subcomponent Damage Functions for Oil Systems

All data in this sub-appendix is sourced from G&E, 1994d.

Table B3-1 Subcomponent Peak Ground Acceleration Fragility Functions for Refineries with Anchored Components

Subcomponent	Damage State	Median (g)	β
Electric Power (Backup)	Slight	0.80	0.60
	Moderate	1.00	0.80
Loss of commercial Power	Slight	0.15	0.40
	Moderate	0.30	0.40
Electrical/Mechanical Equipment	Moderate	1.00	0.60
Tanks	Slight	0.30	0.70
	Moderate	0.70	0.75
	Extensive	1.25	0.75
	Complete	1.60	0.70
Stacks	Extensive	0.75	0.70
Elevated Pipe	Complete	1.00	0.60

Table B3-2 Subcomponent Peak Ground Acceleration Fragility Functions for Refineries with Unanchored Components

Subcomponent	Damage State	Median (g)	β
Electric Power (Backup)	Slight	0.20	0.60
	Moderate	0.40	0.80
Loss of commercial Power	Slight	0.15	0.40
	Moderate	0.30	0.40
Electrical/Mechanical Equipment	Moderate	0.60	0.60
Tanks	Slight	0.15	0.70
	Moderate	0.35	0.75
	Extensive	0.68	0.75
	Complete	0.95	0.70
Stacks	Extensive	0.60	0.70
Elevated Pipe	Complete	1.00	0.60

Table B3-3 Subcomponent Peak Ground Acceleration Fragility Functions for Oil System Pumping Plants with Anchored Components

Subcomponent	Damage State	Median (g)	β
Electric Power (Backup)	Slight	0.80	0.60
	Moderate	1.00	0.80
Loss of commercial Power	Slight	0.15	0.40
	Moderate	0.30	0.40
Vertical/Horizontal Pump[1]	Extensive	1.25/1.60	0.60
Building	Slight	0.15	0.80
	Moderate	0.40	0.80
	Extensive	0.80	0.80
	Complete	1.50	0.80
Electrical/ Mechanical Equipment	Moderate	1.00	0.60

[1] Difference in median values has little effect on the fault tree analysis

Table B3-4 Subcomponent Peak Ground Acceleration Fragility Functions for Oil System Pumping Plants with Unanchored Components

Subcomponent	Damage State	Median (g)	β
Electric Power (Backup)	Slight	0.20	0.60
	Moderate	0.40	0.80
Loss of commercial Power	Slight	0.15	0.40
	Moderate	0.30	0.40
Vertical/Horizontal Pump[1]	Extensive	1.25/1.60	0.60
Building	Slight	0.15	0.80
	Moderate	0.40	0.80
	Extensive	0.80	0.80
	Complete	1.50	0.80
Electrical/Mechanical Equipment	Moderate	0.60	0.60

[1] Difference in median values has little effect on the fault tree analysis

Table B3-5 Subcomponent Peak Ground Acceleration Fragility Functions for Oil System Tank Farms with Anchored Components

Subcomponent	Damage State	Median (g)	β
ElectricPower (Backup)	Slight	0.80	0.60
	Moderate	1.00	0.80
Loss of commercial Power	Slight	0.15	0.40
	Moderate	0.30	0.40
Electrical/Mechanical Equipment	Moderate	1.00	0.60
Tanks	Slight	0.30	0.60
	Moderate	0.70	0.60
	Extensive	1.25	0.65
	Complete	1.60	0.60
Elevated Pipes	Extensive	0.53	0.60
	Complete	1.00	0.60

Table B3-6 Peak Ground Acceleration Subcomponent Fragility Functions for Oil System Tank Farms with Unanchored Components

Subcomponent	Damage State	Median (g)	β
ElectricPower (Backup)	Slight	0.20	0.60
	Moderate	0.40	0.80
Loss of commercial Power	Slight	0.15	0.40
	Moderate	0.30	0.40
Electrical/Mechanical Equipment	Moderate	0.60	0.60
Tanks	Slight	0.15	0.70
	Moderate	0.35	0.75
	Extensive	0.68	0.75
	Complete	0.95	0.70
Elevated Pipes	Extensive	0.53	0.60
	Complete	1.00	0.60

Appendix B4 Subcomponent Damage Functions for Electric Power Systems

All data in this sub-appendix is sourced from G&E, 1994e.

Table B4-1 Peak Ground Acceleration Fragility Functions for Subcomponents of Low Voltage Substations with Anchored Subcomponents

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

[1] Damage state depends on the percentage of the subcomponents failing

Table B4-2 Peak Ground Acceleration Fragility Functions for Subcomponents of Low Voltage Substations with Unanchored Subcomponents

Classification	Damage State	Median (g)	β
Transformer	All[1]	0.50	0.70
Disconnect Switches	All[1]	0.90	0.70
Live Tank Circuit Breaker	All[1]	0.60	0.70
Current Transformer	All[1]	0.75	0.70

[1] Damage state depends on the percentage of the subcomponents failing

Table B4-3 Peak Ground Acceleration Fragility Functions for Subcomponents of Medium Voltage Substations with Anchored Subcomponents

Classification	Damage State	Median (g)	β
Transformer	All[1]	0.60	0.70
Disconnect Switches	All[1]	0.75	0.70
Live Tank Circuit Breaker	All[1]	0.70	0.70
Current Transformer	All[1]	0.50	0.70

[1] Damage state depends on the percentage of the subcomponents failing

Table B4-4 Peak Ground Acceleration Fragility Functions for Subcomponents of Medium Voltage Substations with Anchored Subcomponents

Classification	Damage State	Median (g)	β
Transformer	All[1]	0.30	0.70
Disconnect Switches	All[1]	0.50	0.70
Live Tank Circuit Breaker	All[1]	0.50	0.70
Current Transformer	All[1]	0.50	0.70

[1] Damage state depends on the percentage of the subcomponents failing

Table B4-5 Peak Ground Acceleration Fragility Functions for Subcomponents of High Voltage Substations with Anchored Subcomponents

Classification	Damage State	Median (g)	β
Transformer	All[1]	0.40	0.70
Disconnect Switches	All[1]	0.60	0.70
Live Tank Circuit Breaker	All[1]	0.40	0.70
Current Transformer	All[1]	0.30	0.70

[1] Damage state depends on the percentage of the subcomponents failing

Table B4-6 Peak Ground Acceleration Fragility Functions for Subcomponents of High Voltage Substations with Unanchored Subcomponents

Classification	Damage State	Median (g)	β
Transformer	All[1]	0.25	0.70
Disconnect Switches	All[1]	0.40	0.70
Live Tank Circuit Breaker	All[1]	0.30	0.70
Current Transformer	All[1]	0.30	0.70

[1] Damage state depends on the percentage of the subcomponents failing

Table B4-7 Peak Ground Acceleration Fragility Functions for Distribution Circuits

Classification	Damage State	Median (g)	β
Seismic	All[1]	0.75	0.50
Standard	All[1]	0.60	0.50

[1] Damage state depends on the percentage of the subcomponents failing

Table B4-8 Peak Ground Acceleration Fragility Functions for Subcomponents of Generation Facilities with Anchored Subcomponents

Classification	Damage State	Median (g)	β
Electrical Equipment	Slight	0.30	0.40
	Moderate	0.50	0.60
Boilers & Pressure vessels	Moderate	0.52	0.70
Large vertical vessels with formed heads	Moderate	0.60	0.40
	Extensive	0.88	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	Slight	0.15	0.80
	Moderate	0.40	0.80
	Extensive	0.80	0.80
	Complete	1.50	0.80
Turbine Building	Slight	0.15	0.80
	Moderate	0.40	0.80
	Extensive	0.80	0.80
	Complete	1.50	0.80

Table B4-9 Peak Ground Acceleration Fragility Functions for Subcomponents of Generation Facilities with Unanchored Subcomponents

Classification	Damage State	Median (g)	β
Electrical Equipment	Slight	0.22	0.50
	Moderate	0.35	0.70
Boilers & Pressure vessels	Moderate	0.36	0.70
Large vertical vessels with formed heads	Moderate	0.46	0.50
	Extensive	0.68	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	Slight	0.15	0.80
	Moderate	0.40	0.80
	Extensive	0.80	0.80
	Complete	1.50	0.80
Turbine Building	Slight	0.15	0.80
	Moderate	0.40	0.80
	Extensive	0.80	0.80
	Complete	1.50	0.80

Appendix B5 Subcomponent Damage Functions for Communication Systems

All data in this sub-appendix is sourced from G&E, 1994d.

Table B5-1 Subcomponent Peak Ground Acceleration Fragility Functions for Communication Systems Facilities with Anchored Components

Subcomponent	Damage State	Median (g)	β
Electric Power (Backup)	Slight	0.80	0.60
	Moderate	1.00	0.80
Loss of commercial Power	Slight	0.15	0.40
	Moderate	0.30	0.40
Switching Equipment	Moderate	0.70	0.70
	Extensive	1.00	0.70
	Complete	2.53	0.70
Building	Slight	0.15	0.80
	Moderate	0.40	0.80
	Extensive	0.80	0.80
	Complete	1.50	0.80

Table B5-2 Subcomponent Peak Ground Acceleration Fragility Functions for Communication Systems Facilities with Unanchored Components

Subcomponent	Damage State	Median (g)	β
Electric Power (Backup)	Slight	0.20	0.60
	Moderate	0.40	0.80
Loss of commercial Power	Slight	0.15	0.40
	Moderate	0.30	0.40
Switching Equipment	Moderate	0.45	0.70
	Extensive	0.62	0.70
	Complete	1.58	0.70
Building	Slight	0.15	0.80
	Moderate	0.40	0.80
	Extensive	0.80	0.80
	Complete	1.50	0.80

Appendix C: Transportation and Utility System Subcomponent Information (Damage Ratios & Fraction of Value)

Table C-1 Subcomponents for the Railway System

Subcomponent	Fraction of Total Component Value	Damage State	Damage Ratio
Fuel Facilities			
Electric Backup Power	2%	Slight	0.20
		Moderate	0.70
Tanks	86%	Slight	0.20
		Moderate	0.40
		Extensive	0.85
		Complete	1.00
Pump Building	2%	Slight	0.10
		Moderate	0.40
		Extensive	0.80
		Complete	1.00
Horizontal Pumps	5%	Extensive	0.75
Electrical Equipment	5%	Moderate	0.50
Dispatch Facilities			
Electric Backup Power	30%	Slight	0.20
		Moderate	0.70
Building	20%	Slight	0.10
		Moderate	0.40
		Extensive	0.80
		Complete	1.00
Electrical Equipment	20%	Moderate	0.80

** Source: G&E, 1994b*

Table C-2 Subcomponents for Light Rail DC Substations

Subcomponent	Fraction of Total Component Value	Damage State	Damage Ratio
Building	35%	Slight	0.10
		Moderate	0.40
		Extensive	0.80
		Complete	1.00
Equipment	65%	Moderate	0.80

** Source: G&E, 1994b*

Table C-3 Subcomponent for Potable Water System Components

Subcomponent	Fraction of Total Component Value	Damage State	Damage Ratio
Water Treatment Plant			
Electric Backup Power	4%	Slight	0.20
		Moderate	0.70
Chlorination Equipment	4%	Slight	0.15
		Moderate	0.50
Sediment Flocculation	12%	Slight	0.20
		Moderate	0.50
Chemical Tanks	20%	Slight	0.20
		Moderate	0.75
Electric Equipment	30%	Moderate	0.60
Elevated Pipe	10%	Extensive	0.65
		Complete	0.90
Filter Gallery	20%	Complete	1.00
Wells			
Electric Backup Power	16%	Slight	0.20
		Moderate	0.70
Well Pump	34%	Extensive	0.75
Building	16%	Slight	0.10
		Moderate	0.40
		Extensive	0.80
		Complete	1.00
Electric Equipment	34%	Moderate	0.60
Pumping Plants			
Electric Backup Power	16%	Slight	0.20
		Moderate	0.70
Pumps	34%	Extensive	0.75
Building	16%	Slight	0.10
		Moderate	0.40
		Extensive	0.80
		Complete	1.00
Electrical Equipment	34%	Moderate	0.60

** Source: G&E, 1994c*

Table C-4 Subcomponents for Wastewater Treatment

Subcomponent	Fraction of Total Component Value	Damage State	Damage Ratio
Electric Backup Power	5%	Slight Moderate	0.20 0.70
Chlorination Equipment	3%	Slight Moderate	0.15 0.50
Sediment Flocculation	36%	Slight Moderate Extensive	0.20 0.50 0.80
Chemical Tanks	7%	Slight Moderate	0.20 0.75
Electrical/ Mechanical Equipment	14%	Moderate	0.60
Elevated Pipe	8%	Extensive Complete	0.65 0.90
Buildings	27%	Complete	1.00

** Source: G&E, 1994d*

Table C-5 Subcomponents for Crude & Refined Oil Systems

Subcomponent	Fraction of Total Component Value	Damage State	Damage Ratio
Refineries			
Electric Backup Power	3%	Slight Moderate	0.20 0.70
Electrical/ Mechanical Equipment	6%	Moderate	0.60
Tanks	42%	Slight Moderate Extensive Complete	0.20 0.40 0.85 1.00
Stacks	42%	Extensive	0.80
Elevated Pipe	7%	Complete	1.00
Pumping Plants			
Electric Backup Power	30%	Slight Moderate	0.20 0.70
Pump	20%	Extensive	0.75
Building	20%	Slight Moderate Extensive Complete	0.10 0.40 0.80 1.00

Subcomponent	Fraction of Total Component Value	Damage State	Damage Ratio
Electrical/ Mechanical Equipment	30%	Moderate	0.60
Tank Farms			
Electric Backup Power	6 %	Slight	0.20
		Moderate	0.70
Electrical/ Mechanical Equipment	24 %	Moderate	0.60
Tanks	58 %	Slight	0.20
		Moderate	0.40
		Extensive	0.85
		Complete	1.00
Elevated Pipes	12 %	Extensive	0.65
		Complete	0.90

** Source: G&E, 1994d*

Table C-6 Subcomponents for Electrical Substations

Classification	Fraction of Total Component Value	Damage State	Damage Ratio
Transformers	68%	Extensive	0.50
		Complete	1.00
Circuit Breakers	26%	Slight	0.17
		Moderate	0.33
		Extensive	0.67
		Complete	1.00
Disconnect Switches	3%	Slight	0.17
		Moderate	0.42
		Extensive	0.67
		Complete	1.00
Current Transformers	3%	Extensive	0.67
		Complete	1.00

** Source: G&E, 1994e*

Table C-7 Subcomponents for Generation Plant

Subcomponent	Fraction of Total Component Value	Damage State	Damage Ratio
Electrical Equipment	17%	Slight	0.30
		Moderate	0.60
Boilers & Pressure Vessels	19%	Moderate	0.50
Vertical vessels	5%	Moderate	0.50

Subcomponent	Fraction of Total Component Value	Damage State	Damage Ratio
		Extensive	0.80
Pumps	9%	Extensive	0.75
Horizontal vessels	14%	Complete	1.00
Large motor operated valves	5%	Complete	1.00
Boiler Building	17%	Slight	0.10
		Moderate	0.40
		Extensive	0.80
		Complete	1.00
Turbine Building	14%	Slight	0.10
		Moderate	0.40
		Extensive	0.80
		Complete	1.00

** Source: G&E, 1994e*

Table C-8 Subcomponents for Communication Centers

Subcomponent	Fraction of Total Component Value	Damage State	Damage Ratio
Electric Power (Backup)	15%	Slight	0.20
		Moderate	0.70
Switching Equipment	49%	Slight	0.05
		Moderate	0.20
		Extensive	0.60
		Complete	1.00
Building	36%	Slight	0.10
		Moderate	0.40
		Extensive	0.80
		Complete	1.00

** Source: G&E, 1994d*