EARTHQUAKE LOSS ESTIMATION METHODOLOGY

HAZUS®99

TECHNICAL MANUAL

Developed by:

Federal Emergency Management Agency
Washington, D.C.

Through a cooperative agreement with:

National Institute of Building Sciences
Washington, D.C.

Preface

Earthquakes pose a threat to life and property in 45 states and territories. As the United States has become more urbanized, more frequent smaller earthquakes in the 6.5 to 7.5 Magnitude range now have the potential of causing damage equal to or exceeding the estimated $40 billion from the 1994 Northridge earthquake. Earthquakes in urban areas, such as Kobe, Japan and Izmit, Turkey, are grim reminders of the kind of damage that may result from larger earthquakes, like the San Francisco event of 1906 and eastern events that occurred in New Madrid in 1811-12.

The Federal Emergency Management Agency is committed to mitigation as a means of reducing damages and the social and economic impacts from earthquakes. FEMA, under a Cooperative Agreement with the National Institute of Building Sciences, has developed HAZUS®99 (HAZUS® stands for "Hazards U.S."), the second edition of the standard, nationally-applicable methodology for assessing earthquake risk. Significant enhancements have been added to HAZUS®99, particularly, a disaster response application to facilitate the use of HAZUS® in the immediate post-disaster environment. HAZUS®99 and the preceding edition of the earthquake loss estimation methodology, HAZUS®97, represent the dedicated efforts of more than 130 nationally-recognized earthquake and software professionals.

HAZUS is an important component of FEMA's *Project Impact*, a national movement to create safe and disaster-resistant communities. FEMA is making HAZUS® available to all states and communities, including the almost 200 now participating in *Project Impact*, and the private sector. Communities find HAZUS® to be a valuable tool in promoting a broader understanding of potential earthquake losses and in helping to build a community consensus for disaster loss prevention and mitigation.

Since the first release of HAZUS®, FEMA has been expanding the capability of HAZUS® by initiating loss estimation models for flood and hurricane hazards. Preview versions of these flood and hurricane models are being readied for release in 2002.

I am pleased to disseminate this manual to state and local users.

Michael J. Armstrong
Associate Director for Mitigation
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Foreword

The work that provided the basis for this publication was supported by funding from the Federal Emergency Management Agency (FEMA) under a cooperative agreement with the National Institute of Building Sciences. The substance and findings of that work are dedicated to the public. NIBS is solely responsible for the accuracy of the statements and interpretations contained in this publication. Such interpretations do not necessarily reflect the views of the Federal Government.

The National Institute of Building Sciences (NIBS) is a non-governmental, non-profit organization, authorized by Congress to encourage a more rational building regulatory environment, to accelerate the introduction of existing and new technology into the building process and to disseminate technical information.

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MESSAGE TO USERS

HAZUS is designed to produce loss estimates for use by state, regional and local governments in planning for earthquake loss mitigation, emergency preparedness and response and recovery. The methodology deals with nearly all aspects of the built environment, and with a wide range of different types of losses. The methodology has been tested against the experience from several past earthquakes and against the judgment of experts. Subject to several limitations noted below, HAZUS has been judged capable of producing results that are credible for the intended purposes.

Uncertainties are inherent is any such loss estimation methodology. They arise in part from incomplete scientific knowledge concerning earthquakes and their effect upon buildings and facilities, and in part from the approximations and simplifications necessary for comprehensive analyses. The possible range of uncertainty, possibly a factor or two or more, is best evaluated by conducting multiple analyses, varying certain of the input parameters to which losses are most sensitive. This *User's Manual* gives guidance concerning the planning of such sensitivity studies.

Users should be aware of the following specific limitations:

> HAZUS is most accurate when applied to a class of buildings or facilities, and least accurate if applied to a particular building or facility.
>
> Accuracy of losses associated with lifelines may be less than for losses associated with the general building stock.
>
> Based on several initial abbreviated tests, the losses from small magnitude (less than M 6.0) earthquakes appear to be overestimated.
>
> Uncertainty related to the characteristics of ground motion in the Eastern U.S. is high. Conservative treatment of this uncertainty may lead to overestimation of losses in this area, both for scenario events and when using probabilistic ground motion.
>
> Pilot and calibration studies have as yet not provided an adequate test concerning the possible extent and effects of landslides and the performance of water systems.
>
> The indirect economic loss module is new and experimental. While output from pilot studies has generally been credible, this module requires further testing.

HAZUS should be regarded as a work in progress. Additional improvements and increased confidence will come with further experience in using HAZUS. To assist us in further improving HAZUS, users are invited to submit comments on methodological and software issues by letter, fax or e-mail to:

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What is New in HAZUS99?

- The ground motion model has been revised by implementing new algorithms for calculating the distance to the fault rupture plane and accounting for earthquakes that rupture across multiple fault segments. New attenuation functions have been added for Hawaii (Munson & Thurber) and the Eastern United States (Lawrence Livermore National Lab). Details of these changes are included in Chapter 4 of the *Technical Manual*.

- A new bridge model based on the nonlinear performance of bridges has been implemented along with a revised bridge classification scheme and updated national bridge inventory. Details of these changes are included in Chapter 7 of the Technical Manual.

- For the probabilistic analysis of building damage, revised fragility curves have been added that are compatible with the USGS probabilistic ground motion maps. These new fragility curves, however, are still under review by the Earthquake Committee. In addition, **HAZUS99** now has the capability to automatically compute annualized loss estimates for buildings. Details of these changes are included in Chapters 5 and 16 of the *Technical Manual*.

- HAZUS99 now includes a network analysis model for potable water systems. Although the model is fully functional, the results generated are still under review by the Utility Lifeline Subcommittee. Details of these changes are included in Chapter 8 of the *Technical Manual*.

- The indirect economic loss model has been improved to accommodate weekly and monthly inputs in the first two years after an earthquake event. Details of these changes are included in Chapter 16 of the *Technical Manual*.

- **HAZUS99** includes a new application that can directly link **HAZUS** with Tri-NET. This capability will allow **HAZUS** to monitor Tri-NET and to automatically create a study region and execute the analysis when an earthquake is broadcast. In addition, **HAZUS99** response and recovery capabilities have been enhanced with the addition of a "ground truthing" option. This special feature allows users to incorporate observed damage information for use in post-event operational response. Details of these changes are included in Chapter 9 and 12 of the *User's Manual*.

- **HAZUS99** has been optimized for greater speed.

- In addition to several new summary reports, a comprehensive summary report of analysis results has been added. The report, about 20 pages in length, contains text and tabular data about the study region, the earthquake scenario selected, and the results.

- The capability to save and recall map workspaces has been added.

- Several databases in HAZUS99 have been added: updated USGS probabilistic ground motion maps and US source maps, a revised hospital database, a new national bridge inventory, an updated hazardous material site database and a new national railroad track database.

Chapter 7
Direct Physical Damage to Lifelines - Transportation Systems

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

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

The flowchart of the overall methodology, highlighting the transportation system module and its relationship to other modules, is shown in Flowchart 7.1.

7.1 Highway Transportation System

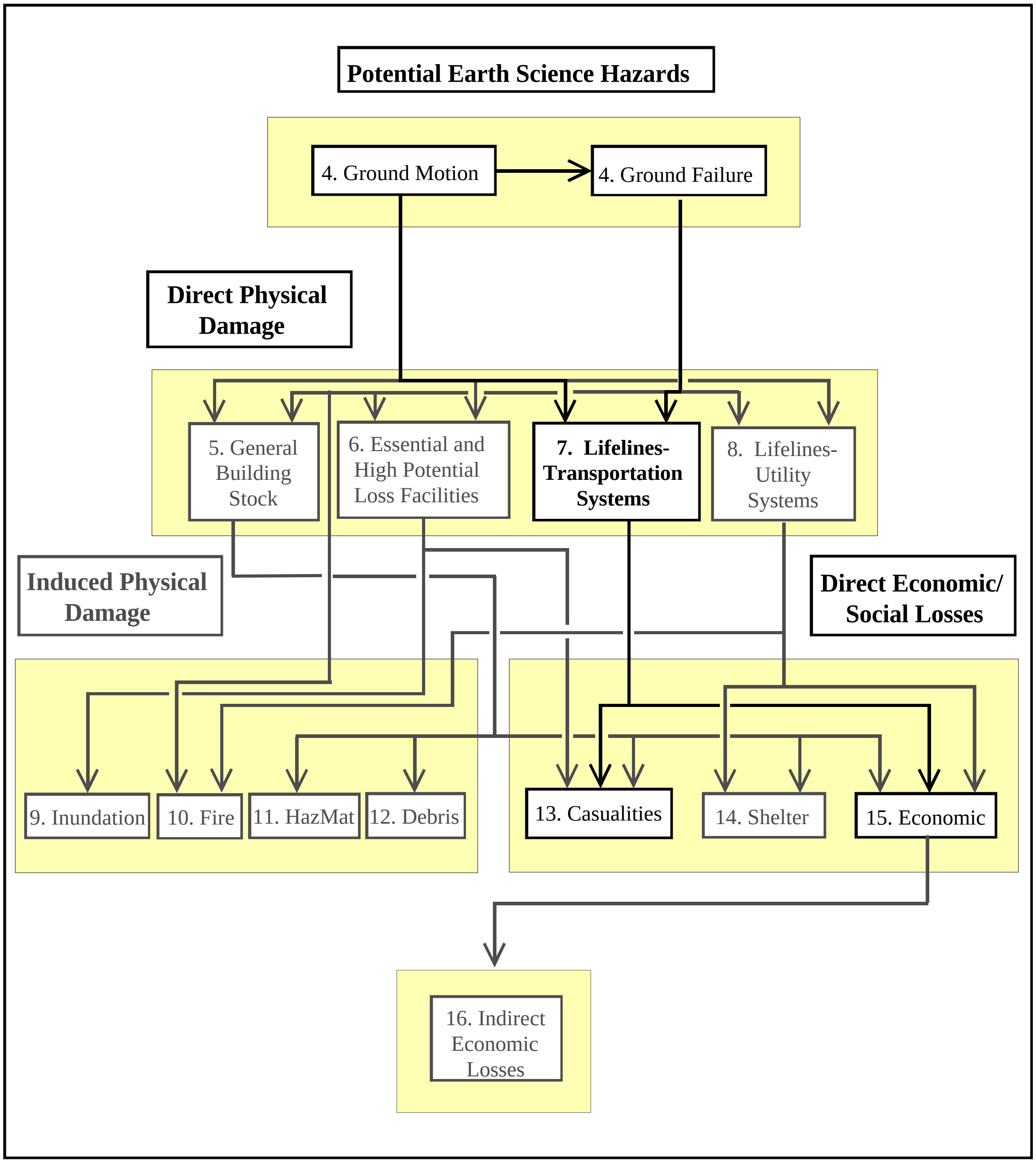
7.1.1 Introduction

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

7.1.2 Scope

The scope of this section includes development of methods for estimation of earthquake damage to a highway transportation system given knowledge of the system's components (i.e., roadways, bridges, or tunnels), the classification of each component (e.g., for roadways, whether the road is a major road or urban road), and the ground motion (i.e. peak ground acceleration and/or permanent ground deformation).

Damage states describing the level of damage to each highway system component are defined (i.e. slight/minor, moderate, extensive or complete). Damage states are related to a damage ratio defined as the ratio of repair to replacement cost for evaluation of direct economic loss. Component restoration curves are provided for each damage state to evaluate loss of function. Restoration curves describe the fraction or percentage of the component that is expected to be open or operational as a function of time following the earthquake. For example, an extensively damaged roadway link might be closed (0% functional) immediately following the earthquake, but 100% functional after 30 days.



Flowchart 7.1 Transportation System Damage Relationship to Other Modules of the Earthquake Loss Estimation Methodology

Fragility curves are developed for each type of highway system component. These curves describe the probability of reaching or exceeding each damage state given the level of ground motion.

7.1.3 Input Requirements and Output Information

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

Roadways

- Geographical location of roadway links (longitude and latitude of end nodes)
- Permanent ground deformation (PGD) at roadway link
- Roadway classification

Bridges

- Geographical location of bridge [longitude and latitude]
- Bridge classification
- Spectral accelerations at 0.3 sec and 1.0 sec, and PGD at bridge
- Peak Ground Acceleration (for PGD-related computations)

Tunnels

- Geographical location of tunnels [longitude and latitude]
- PGA and PGD at tunnel
- Tunnel Classification

Direct damage output for highway systems includes probability estimates of (1) component functionality and (2) physical damage expressed in terms of the component's damage ratio. Note that damage ratios, which are input to direct economic loss methods, are described in Chapter 15.

Component functionality is described by the probability of damage state (immediately following the earthquake) and by the associated fraction or percentage of the component that is expected to be functional after a specified period of time. For example, a roadway link might be found to have a 0.50 probability of extensive damage and on this basis would have a 0.50 probability that the road would be: (1) closed immediately, (2) partially open after a 3-day restoration period and (3) fully open after a 1-month restoration period.

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

7.1.4 Form of Damage Functions

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

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

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

7.1.5 Description of Highway Components

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

Roadways

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

Bridges

Bridges are classified based on the following structural characteristics:

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

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

This classification scheme incorporates various parameters that affect damage into fragility analysis and provides a means to obtain better fragility curves when data become available. A total of 28 classes (HWB1 through HWB28) are defined this way. These classes differentiate between the different bridge characteristics found in the National Bridge Inventory (NBI).

Tables 7.1.a and 7.1.b summarize the key NBI characteristics used, while Table 7.2 presents the 28 classes derived for HAZUS. Please refer to Table 3.6 in Chapter 3 for the full definitions of these bridges.

Table 7.1.a Bridge material Classes in NBI [NBI, 1988]

Code	Description
1	Concrete
2	Concrete continuous
3	Steel
4	Steel continuous
5	Prestressed concrete
6	Prestressed concrete continuous
7	Timber
8	Masonry
9	Aluminium, Wrought Iron, or Cast Iron
0	Other

Table 7.1.b Bridge Types in NBI [NBI, 1988]

Code	Description
01	Slab
02	Stringer/Multi-beam or Girder
03	Girder and Floor beam System
04	Tee Beam
05	Box Beam or Girders - Multiple
06	Box Beam or Girders – single or Spread
07	Frame
08	Orthotropic
09	Truss – Deck
10	Truss – Thru
11	Arch – Deck
12	Arch – Thru
13	Suspension
14	Stayed Girder
15	Movable – Lift
16	Movable – Bascule
17	Movable – Swing
18	Tunnel
19	Culvert
20	Mixed Types (applicable only to approach spans)
21	Segmental Box Girder
22	Channel Beam
00	Other

Table 7.2 HAZUS Bridge Classification Scheme

CLASS	NBI Class	State	Year Built	# Spans	Length of Max. Span (meter)	Length less than 20 m	K_{3D} (See note below)	I_{shape} (See note below)	Design	Description
HWB1	All	Non-CA	< 1990		> 150	N/A	EQ1	0	Conventional	Major Bridge - Length > 150m
HWB1	All	CA	< 1975		> 150	N/A	EQ1	0	Conventional	Major Bridge - Length > 150m
HWB2	All	Non-CA	>= 1990		> 150	N/A	EQ1	0	Seismic	Major Bridge - Length > 150m
HWB2	All	CA	>= 1975		> 150	N/A	EQ1	0	Seismic	Major Bridge - Length > 150m
HWB3	All	Non-CA	< 1990	1		N/A	EQ1	1	Conventional	Single Span
HWB3	All	CA	< 1975	1		N/A	EQ1	1	Conventional	Single Span
HWB4	All	Non-CA	>= 1990	1		N/A	EQ1	1	Seismic	Single Span
HWB4	All	CA	>= 1975	1		N/A	EQ1	1	Seismic	Single Span
HWB5	101-106	Non-CA	< 1990			N/A	EQ1	0	Conventional	Multi-Col. Bent, Simple Support - Concrete
HWB6	101-106	CA	< 1975			N/A	EQ1	0	Conventional	Multi-Col. Bent, Simple Support - Concrete
HWB7	101-106	Non-CA	>= 1990			N/A	EQ1	0	Seismic	Multi-Col. Bent, Simple Support - Concrete
HWB7	101-106	CA	>= 1975			N/A	EQ1	0	Seismic	Multi-Col. Bent, Simple Support - Concrete
HWB8	205-206	CA	< 1975			N/A	EQ2	0	Conventional	Single Col., Box Girder - Continuous Concrete
HWB9	205-206	CA	>= 1975			N/A	EQ3	0	Seismic	Single Col., Box Girder - Continuous Concrete
HWB10	201-206	Non-CA	< 1990			N/A	EQ2	1	Conventional	Continuous Concrete
HWB10	201-206	CA	< 1975			N/A	EQ2	1	Conventional	Continuous Concrete
HWB11	201-206	Non-CA	>= 1990			N/A	EQ3	1	Seismic	Continuous Concrete
HWB11	201-206	CA	>= 1975			N/A	EQ3	1	Seismic	Continuous Concrete
HWB12	301-306	Non-CA	< 1990			No	EQ4	0	Conventional	Multi-Col. Bent, Simple Support - Steel
HWB13	301-306	CA	< 1975			No	EQ4	0	Conventional	Multi-Col. Bent, Simple Support - Steel
HWB14	301-306	Non-CA	>= 1990			N/A	EQ1	0	Seismic	Multi-Col. Bent, Simple Support - Steel
HWB14	301-306	CA	>= 1975			N/A	EQ1	0	Seismic	Multi-Col. Bent, Simple Support - Steel
HWB15	402-410	Non-CA	< 1990			No	EQ5	1	Conventional	Continuous Steel
HWB15	402-410	CA	< 1975			No	EQ5	1	Conventional	Continuous Steel
HWB16	402-410	Non-CA	>= 1990			N/A	EQ3	1	Seismic	Continuous Steel
HWB16	402-410	CA	>= 1975			N/A	EQ3	1	Seismic	Continuous Steel

Table 7.2 HAZUS Bridge Classification Scheme (Continued)

CLASS	NBI Class	State	Year Built	# Spans	Length of Max. Span (meter)	Length less than 20 m	K_{3D} (See note below)	I_{shape} (See note below)	Design	Description
HWB17	501-506	Non-CA	< 1990			N/A	EQ1	0	Conventional	Multi-Col. Bent, Simple Support - Prestressed Concrete
HWB18	501-506	CA	< 1975			N/A	EQ1	0	Conventional	Multi-Col. Bent, Simple Support - Prestressed Concrete
HWB19	501-506	Non-CA	>= 1990			N/A	EQ1	0	Seismic	Multi-Col. Bent, Simple Support - Prestressed Concrete
HWB19	501-506	CA	>= 1975			N/A	EQ1	0	Seismic	Multi-Col. Bent, Simple Support - Prestressed Concrete
HWB20	605-606	CA	< 1975			N/A	EQ2	0	Conventional	Single Col., Box Girder - Prestressed Continuous Concrete
HWB21	605-606	CA	>= 1975			N/A	EQ3	0	Seismic	Single Col., Box Girder - Prestressed Continuous Concrete
HWB22	601-607	Non-CA	< 1990			N/A	EQ2	1	Conventional	Continuous Concrete
HWB22	601-607	CA	< 1975			N/A	EQ2	1	Conventional	Continuous Concrete
HWB23	601-607	Non-CA	>= 1990			N/A	EQ3	1	Seismic	Continuous Concrete
HWB23	601-607	CA	>= 1975			N/A	EQ3	1	Seismic	Continuous Concrete
HWB24	301-306	Non-CA	< 1990			Yes	EQ6	0	Conventional	Multi-Col. Bent, Simple Support - Steel
HWB25	301-306	CA	< 1975			Yes	EQ6	0	Conventional	Multi-Col. Bent, Simple Support - Steel
HWB26	402-410	Non-CA	< 1990			Yes	EQ7	1	Conventional	Continuous Steel
HWB27	402-410	CA	< 1975			Yes	EQ7	1	Conventional	Continuous Steel
HWB28										All other bridges that are not classified

Note that EQ1 through EQ7 in Table 7.2 are equations for evaluating K_{3D}, which is a factor that modifies the piers' 2-dimensional capacity allowing for 3-dimensional arch action in the deck. All these equations have the functional form of:

$$K_{3D} = 1 + A / (N - B)$$

Where N is the number of spans and A and B are given in table 7.3.

Also note that I_{shape} in table 7.2 is a Boolean indicator. When $I_{shape} = 0$, then the K_{shape} factor, which is a modifier that converts cases for short periods to an equivalent spectral amplitude at T=1.0 second, does not apply. On the other hand, When $I_{shape} = 1$, then the K_{shape} factor applies. Later in this section, the use of the K_{shape} factor will be illustrated through an example.

It is important to remember that the 28 bridge classes in Table 7.2 (HWB1 through HWB28) reflect the maximum number of combinations for 'standard' bridge classes. Attributes such as the skeweness and number of spans are further accounted for in the evaluation of damage potential through a modification scheme that is presented later in this section.

Table 7.3 Coefficients for Evaluating K_{3D}

Equation	A	B	K_{3D}
EQ1	0.25	1	1 + 0.25 / (N – 1)
EQ2	0.33	0	1 + 0.33 / (N)
EQ3	0.33	1	1 + 0.33 / (N – 1)
EQ4	0.09	1	1 + 0.09 / (N – 1)
EQ5	0.05	0	1 + 0.05 / (N)
EQ6	0.20	1	1 + 0.20 / (N – 1)
EQ7	0.10	0	1 + 0.10 / (N)

Tunnels

Tunnels are classified as bored/drilled or cut & cover.

7.1.6 Definitions of Damage States

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

Slight/Minor Damage (ds_2)

- For roadways, ds_2 is defined by slight settlement (few inches) or offset of the ground.

- For bridges, ds_2 is defined by minor cracking and spalling to the abutment, cracks in shear keys at abutments, minor spalling and cracks at hinges, minor spalling at the column (damage requires no more than cosmetic repair) or minor cracking to the deck

- For tunnels, ds_2 is defined by minor cracking of the tunnel liner (damage requires no more than cosmetic repair) and some rock falling, or by slight settlement of the ground at a tunnel portal.

Moderate Damage (ds_3)

- For roadways, ds_3 is defined by moderate settlement (several inches) or offset of the ground.

- For bridges, ds_3 is defined by any column experiencing moderate (shear cracks) cracking and spalling (column structurally still sound), moderate movement of the abutment (<2"), extensive cracking and spalling of shear keys, any connection having cracked shear keys or bent bolts, keeper bar failure without unseating, rocker bearing failure or moderate settlement of the approach.

- For tunnels, ds_3 is defined by moderate cracking of the tunnel liner and rock falling.

Extensive Damage (ds_4)

- For roadways, ds_4 is defined by major settlement of the ground (few feet).

- For bridges, ds_4 is defined by any column degrading without collapse – shear failure - (column structurally unsafe), significant residual movement at connections, or major settlement approach, vertical offset of the abutment, differential settlement at connections, shear key failure at abutments.

- For tunnels, ds_4 is characterized by major ground settlement at a tunnel portal and extensive cracking of the tunnel liner.

Complete Damage (ds_5)

- For roadways, ds_5 is defined by major settlement of the ground (i.e., same as ds_4).

- For bridges, ds_5 is defined by any column collapsing and connection losing all bearing support, which may lead to imminent deck collapse, tilting of substructure due to foundation failure.

- For tunnels, ds_5 is characterized by major cracking of the tunnel liner, which may include possible collapse.

7.1.7 Component Restoration Curves

Restoration curves are developed based on a best fit to ATC-13 data for the social function classifications of interest (SF 25a through SF 25e) consistent with damage states defined in the previous section (first four classes in ATC-13). Figure 7.1 shows restoration curves for urban and major roads, Figure 7.2 represents restoration curves for highway bridges, while Figure 7.3 shows restoration curves for highway tunnels. The smooth curves shown in these figures are normal curves characterized by a mean and a standard deviation. The parameters of these restoration curves are given in Tables 7.4 and 7.5. The former table gives means and standard deviations for each restoration curve (i.e., smooth continuous curve), while the second table gives approximate discrete functions for the restoration curves developed.

Table 7.4 Continuous Restoration Functions for Highways (after ATC-13, 1985)

Damage State	Roadways		Highway Bridges		Highway Tunnels	
	Mean (Days)	σ (days)	Mean (Days)	σ (days)	Mean (Days)	σ (days)
Slight/Minor	0.9	0.05	0.6	0.6	0.5	0.3
Moderate	2.2	1.8	2.5	2.7	2.4	2.0
Extensive	21	16	75.0	42.0	45.0	30.0
Complete			230.0	110.0	210.0	110.0

The values shown in Table 7.5 below represent distributions on functionality for each restoration period based on damage state immediately after the earthquake.

Table 7.5 Discrete Restoration Functions for Highways

Roadways

Restoration Period	Functional Percentage		
	Slight	Moderate	Extensive/Complete
1 day	90	25	10
3 days	100	65	14
7 days	100	100	20
30 days	100	100	70
90 days	100	100	100

Bridges

Restoration Period	Functional Percentage			
	Slight	Moderate	Extensive	Complete
1 day	70	30	2	0
3 days	100	60	5	2
7 days	100	95	6	2
30 days	100	100	15	4
90 days	100	100	65	10

Tunnels

Restoration Period	Functional Percentage			
	Slight	Moderate	Extensive	Complete
1 day	90	25	5	0
3 days	100	65	8	3
7 days	100	100	10	3
30 days	100	100	30	5
90 days	100	100	95	15

7.1.8 Development of Damage Functions

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

Damage functions for Roadways

Fragility curves for major roads and urban roads are shown in Figures 7.4. and 7.5, respectively. The medians and dispersions of these curves are presented in Table 7.6.

Table 7.6 Damage Algorithms for Roadways

Permanent Ground Deformation			
Components	**Damage State**	**Median (in)**	**β**
Major Road (Hrd1)	slight/minor	12	0.7
	moderate	24	0.7
	extensive/complete	60	0.7
Urban Roads (Hrd2)	slight/minor	6	0.7
	moderate	12	0.7
	extensive/complete	24	0.7

Damage Functions for Bridges

There are 28 primary bridge types for which all four damage states are identified and described. For other bridges, fragility curves of the 28 primary bridge types are adjusted to reflect a diminished or improved level of expected performance.

A total of 224 bridge damage functions are obtained, 116 due to ground shaking and 116 due to ground failure. For more information on the theoretical background in the derivation of these fragility curves, consult the work done by ***Basoz and Mander (1999)***, which is referenced at the end of this section and which can obtained from NIBS.

Medians of these damage functions are given in Table 7.7. Note that the dispersion is set to 0.4 for the ground shaking damage algorithm and 0.2 for the ground failure damage algorithm. Also note that only incipient unseating and collapse (i.e., which correspond to extensive and complete damage states) are considered as the possible types of damage due to ground failure. That is, initial damage to bearings (i.e., which would correspond to slight and/or moderate damage states) from ground failure is not considered.

Figures 7.6 and 7.7 show example fragility curves for major bridges.

Table 7.7 Damage Algorithms for Bridges

	Sa [1.0 sec in g's] for Damage Functions due to Ground Shaking				PGD [inches] for Damage Functions due to Ground Failure			
CLASS	Slight	Moderate	Extensive	Complete	Slight	Moderate	Extensive	Complete
HWB1	0.4	0.5	0.6	0.8	7.9	7.9	7.9	15.7
HWB2	0.6	0.8	1	1.6	31.5	31.5	31.5	35.4
HWB3	0.8	0.9	1.1	1.6	3.9	3.9	3.9	17.7
HWB4	0.8	0.9	1.1	1.6	3.9	3.9	3.9	17.7
HWB5	0.26	0.35	0.44	0.65	3.9	3.9	3.9	13.8
HWB6	0.33	0.46	0.56	0.83	3.9	3.9	3.9	13.8
HWB7	0.45	0.76	1.05	1.53	3.9	3.9	3.9	13.8
HWB8	0.35	0.42	0.5	0.74	3.9	3.9	3.9	5.9
HWB9	0.54	0.88	1.22	1.45	23.6	23.6	23.6	35.4
HWB10	0.6	0.79	1.05	1.38	3.9	3.9	3.9	5.9
HWB11	0.91	0.91	1.05	1.38	23.6	23.6	23.6	35.4
HWB12	0.26	0.35	0.44	0.65	3.9	3.9	3.9	13.8
HWB13	0.33	0.46	0.56	0.83	3.9	3.9	3.9	13.8
HWB14	0.45	0.76	1.05	1.53	3.9	3.9	3.9	13.8
HWB15	0.76	0.76	0.76	1.04	3.9	3.9	3.9	9.8
HWB16	0.91	0.91	1.05	1.38	5.9	5.9	5.9	11.8
HWB17	0.26	0.35	0.44	0.65	3.9	3.9	3.9	13.8
HWB18	0.33	0.46	0.56	0.83	3.9	3.9	3.9	13.8
HWB19	0.45	0.76	1.05	1.53	3.9	3.9	3.9	13.8
HWB20	0.35	0.42	0.5	0.74	3.9	3.9	3.9	5.9
HWB21	0.54	0.88	1.22	1.45	23.6	23.6	23.6	35.4
HWB22	0.6	0.79	1.05	1.38	3.9	3.9	3.9	5.9
HWB23	0.91	0.91	1.05	1.38	23.6	23.6	23.6	35.4
HWB24	0.26	0.35	0.44	0.65	3.9	3.9	3.9	13.8
HWB25	0.33	0.46	0.56	0.83	3.9	3.9	3.9	13.8
HWB26	0.76	0.76	0.76	1.04	3.9	3.9	3.9	9.8
HWB27	0.76	0.76	0.76	1.04	3.9	3.9	3.9	9.8
HWB28	0.8	0.9	1.1	1.6	3.9	3.9	3.9	17.7

The damage algorithm for bridges can be broken into seven steps:

Step 1:
Get the bridge location (longitude and latitude), class (HWB1 through HWB28), number of spans (N), skew angle (α), span width (W), bridge length (L), and maximum span length (L_{max}). Note that the skew angle is defined as the angle between the centerline of a pier and a line normal to the roadway centerline.

Step 2:
Evaluate the soil-amplified shaking at the bridge site. That is, get the peak ground acceleration (PGA), spectral accelerations (Sa[0.3 sec] and Sa[1.0 sec]) and the permanent ground deformation (PGD).

Step 3:
Evaluate the following three modification factors:

K_{skew} = sqrt[sin(90-α)]

K_{shape} = 2.5 x Sa(1.0 sec) / Sa(0.3 sec)

K_{3D} = 1 + A / (N – B)   A and B are read from Table 7.3

Step 4:
Modify the ground shaking medians for the "standard" fragility curves in Table 7.7 as follows:

New Median [for slight] = Old Median [for slight] x $Factor_{slight}$

Where
$Factor_{slight}$ = 1 if I_{shape} = 0 (I_{shape} is read from Table 7.2)
or
$Factor_{slight}$ = minimum of (1, K_{shape}) if I_{shape} = 1

New median [moderate] = Old median [for moderate] * (K_{skew}) * (K_{3D})

New median [extensive] = Old median [for extensive] * (K_{skew}) * (K_{3D})

New median [complete] = Old median [for complete] * (K_{skew}) * (K_{3D})

Step 5:
Use the new medians along with the dispersion β = 0.4 to evaluate the ground shaking-related damage state probabilities. Note that Sa(1.0 sec) is the parameter to use in this evaluation.

Step 6:
Evaluate the ground failure-related damage state probabilities. Note that the PGD medians listed in Table 7 will need to be adjusted as follows:

New PGD median [for slight] = ‘Table7.7’ PGD median [for slight] x f_1
New PGD median [moderate] = ‘Table7.7’ PGD median [for moderate] x f_1
New PGD median [extensive] = ‘Table7.7’ PGD median [for extensive] x f_1
New PGD median [complete] = ‘Table7.7’ median [for complete] x f_2

Where f_1 and f_2 are modification factors that are functions of the number of spans (N), width of the span (W), length of the bridge (L), and the skewness (α) and can be computed using the equations in Table 7.8 below.

Table 7.8 Modifiers for PGD Medians

CLASS	f_1	f_2
HWB1	1	1
HWB2	1	1
HWB3	1	1
HWB4	1	1
HWB5	0.5 * L / [N . W . sin (α)]	0.5 * L / [N . W . sin (α)]
HWB6	0.5 * L / [N . W . sin (α)]	0.5 * L / [N . W . sin (α)]
HWB7	0.5 * L / [N . W . sin (α)]	0.5 * L / [N . W . sin (α)]
HWB8	1	sin (α)
HWB9	1	sin (α)
HWB10	1	sin (α)
HWB11	1	sin (α)
HWB12	0.5 * L / [N . W . sin (α)]	0.5 * L / [N . W . sin (α)]
HWB13	0.5 * L / [N . W . sin (α)]	0.5 * L / [N . W . sin (α)]
HWB14	0.5 * L / [N . W . sin (α)]	0.5 * L / [N . W . sin (α)]
HWB15	1	sin (α)
HWB16	1	sin (α)
HWB17	0.5 * L / [N . W . sin (α)]	0.5 * L / [N . W . sin (α)]
HWB18	0.5 * L / [N . W . sin (α)]	0.5 * L / [N . W . sin (α)]
HWB19	0.5 * L / [N . W . sin (α)]	0.5 * L / [N . W . sin (α)]
HWB20	1	sin (α)
HWB21	1	sin (α)
HWB22	0.5 * L / [N . W . sin (α)]	0.5 * L / [N . W . sin (α)]
HWB23	0.5 * L / [N . W . sin (α)]	0.5 * L / [N . W . sin (α)]
HWB24	0.5 * L / [N . W . sin (α)]	0.5 * L / [N . W . sin (α)]
HWB25	0.5 * L / [N . W . sin (α)]	0.5 * L / [N . W . sin (α)]
HWB26	1	sin (α)
HWB27	1	sin (α)
HWB28	1	1

Step 7:

Combine the damage state probabilities and evaluate functionality of bridge.

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

Sa(0.3 sec) = 2.1g, Sa(1.0 sec) = 0.24g PGA = 0.38g

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

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

First, the ground motion data is amplified for soil conditions (Table 4.10 in Chapter 4):

Sa(0.3 sec) = 2.1g (1 x 2.1g),
Sa(1.0 sec) = 0.43g (1.8 x 0.24g)
PGA = 0.53g (1.4 x 0.38g)

Second, the bridge gets classified.

Bridge data necessary for the analysis

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

HAZUS default class for this bridge based on the information above is **HWB17**

Next, the parameters needed in evaluating the median spectral accelerations are computed:

Step 3:

K_{skew} = sqrt[sin(90-α)] =sqrt [sin (90 – 32)] = 0.91

K_{shape} = 2.5 x Sa(1.0 sec) / Sa(0.3 sec) = 0.5

K_{3D} = 1 + A / (N – B) = 1 + 0.25 / (3-1) = 1.125 (See Tables 7.2 and 7.3)

Step 4:

From Table 7.2, I_{shape} is 0 for HWB17, therefore "long periods" governs, and $Factor_{slight}$ is 1. Therefore:

New Sa[1.0 sec] [for slight] = Old Sa[1.0 sec] [for slight] x $Factor_{slight}$
= 0.26g x 1 = 0.26g
New Sa[1.0 sec] [moderate] = Old Sa[1.0 sec] [for moderate] * (K_{skew}) * (K_{3D})
= 0.35g x 0.91 x 1.125 = 0.36g
New Sa[1.0 sec] [extensive] = Old Sa[1.0 sec] [for extensive] * (K_{skew}) * (K_{3D})
= 0.44g x 0.91 x 1.125 = 0.45g
New Sa[1.0 sec] [complete] = Old Sa[1.0 sec] [for complete] * (K_{skew}) * (K_{3D})
= 0.65g x 0.91 x 1.125 = 0.67g

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 0.4):

P[No damage] = 1 – 0.90 = 0.10
P[Slight damage] = 0.90 – 0.67 = 0.23
P[Moderate damage] = 0.67 – 0.46 = 0.21
P[Extensive damage] = 0.46 – 0.13 = 0.33
P[Complete damage] = 0.13

Damage Functions for Tunnels

Tunnel damage functions are based on the damage functions of their subcomponents, namely the liner and the portal (G&E, 1994). G&E findings are based partly on earthquake experience data reported by Dowding et. al. (1978) and Owen et. al (1981). These subcomponent damage functions are given in Tables A.7.1 and A.7.2.

A total of ten tunnel damage functions are obtained, four due to PGA and six due to PGD (i.e., if each class of tunnel is considered separately). Medians and dispersion factors of these damage functions are given in Table 7.9.

Table 7.9 Damage Algorithms for Tunnels (after G&E, 1994)

Peak Ground Acceleration			
Classification	**Damage State**	**Median (g)**	**β**
Bored/Drilled (HTU1)	slight/minor moderate	0.6 0.8	0.6 0.6
Cut & Cover (HTU2)	slight/minor moderate	0.5 0.7	0.6 0.6

Permanent Ground Deformation			
Classification	**Damage State**	**Median (in)**	**β**
All Tunnels	slight/moderate extensive complete	6.0 12.0 60.0	0.7 0.5 0.5

Graphical representations of these damage functions are also provided. Figures 7.8 and Figure 7.9 plot fragility curves due to PGA for bored/drilled and cut & cover tunnels, respectively, while Figure 7.10 presents fragility curves for tunnels due to PGD.

7.1.9 Guidance for Loss Estimation Using Advanced Data and Models Analysis

For this level of analysis, the expert can use the methodology developed with the flexibility to (1) include a more refined inventory of the transportation system pertaining to the area of study, and (2) include component-specific and system-specific fragility data. User-supplied damage algorithms can be modified, or replaced, to incorporate improved information about key components of a highway system, such as a major bridge. Similarly, better restoration curves can be developed, given knowledge of available resources and a more accurate layout of the transportation network within the local topographic and geological conditions (i.e., if the redundancy and importance of highway components of the network are known).

7.1.10 References

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

(2) Dowding, C.H. and Rozen, A., "Damage to Rock Tunnels from Earthquake Shaking", *Journal of the Geotechnical Engineering Division*, American Society of Civil Engineers, New York, NY, February 1978.

(3) National Institute of Building Sciences, “Enhancement of the Highway Transportation Lifeline Module in HAZUS”, prepared by Nesrin Basoz and John Mander, January 1999.

(4) Kim, S.H., "A GIS-Based Regional Risk Analysis Approach for Bridges against Natural Hazards", a dissertation submitted to the faculty of the graduate school of the State University of New York at Buffalo, September 1993.

(5) Owen, G.N. and Scholl, R.E., "Earthquake Engineering Analysis of a Large Underground Structures", Federal Highway Administration and National Science Foundation, FHWA/RD-80/195, January 1981.

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

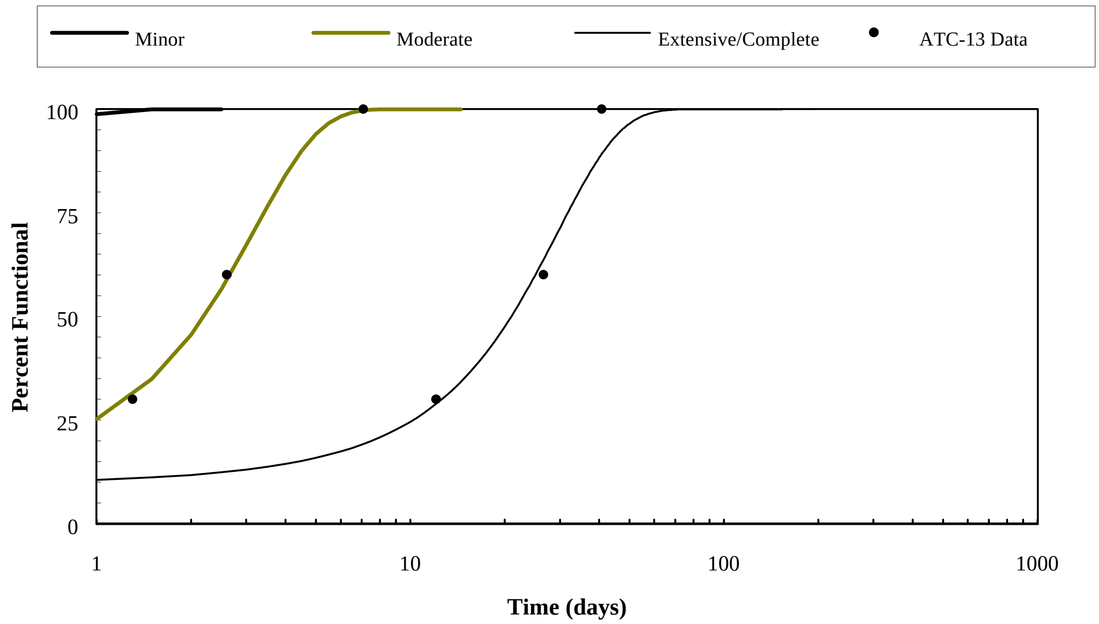


Figure 7.1 Restoration Curves for Urban and Major Roads (after ATC-13, 1985).

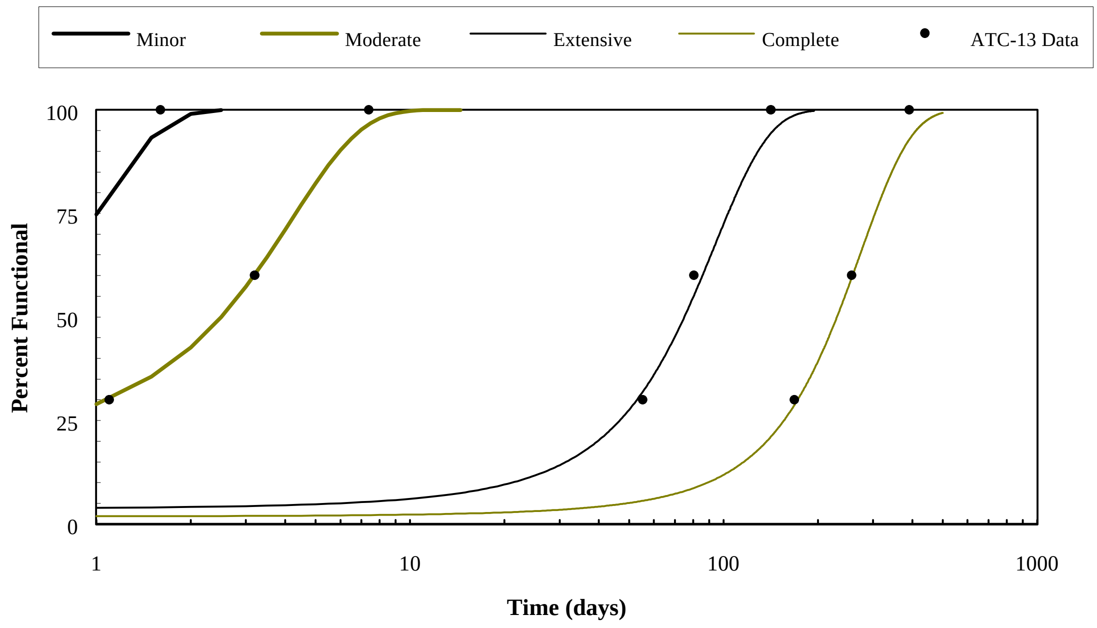


Figure 7.2 Restoration Curves for Highway Bridges (after ATC-13, 1985).

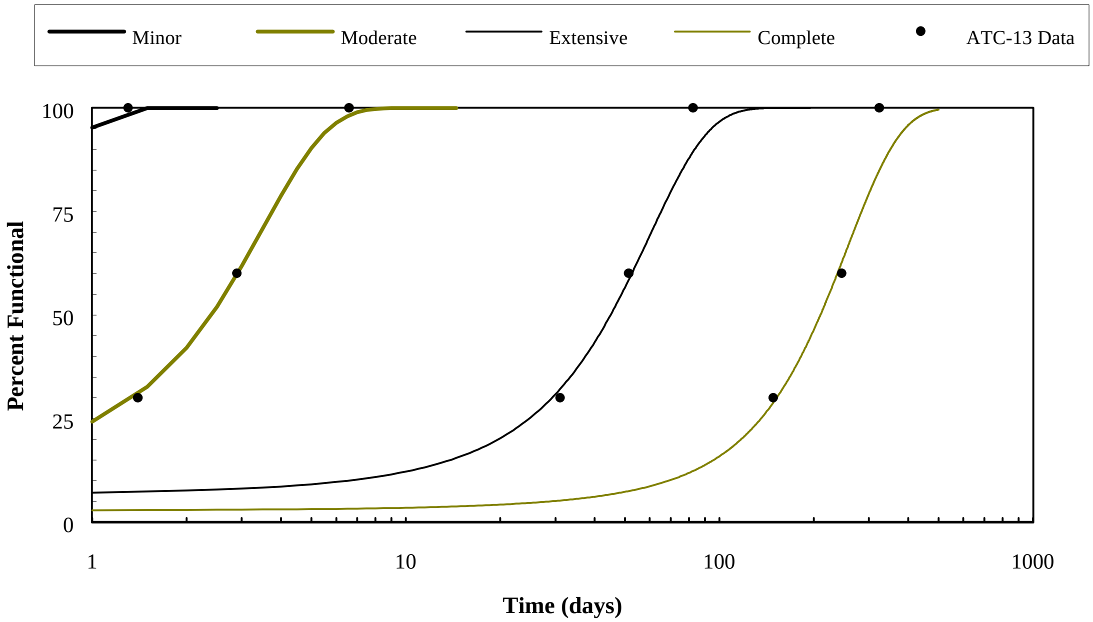


Figure 7.3 Restoration Curves for Highway Tunnels (after ATC-13, 1985).

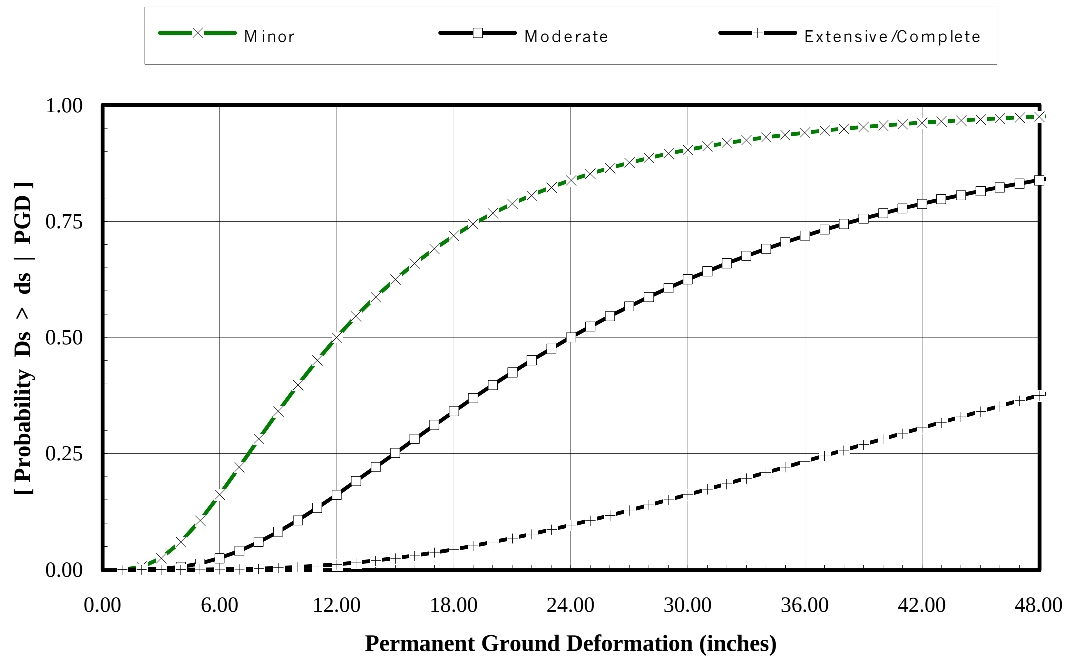


Figure 7.4 Fragility Curves at Various Damage States for Interstate and State Highways.

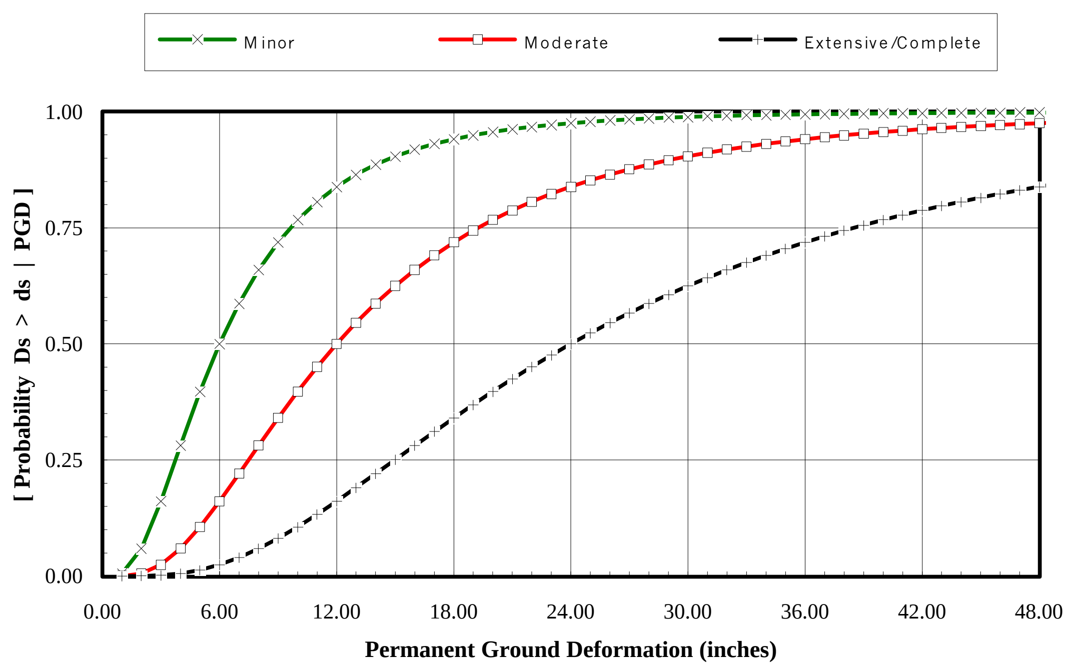


Figure 7.5 Fragility Curves at Various Damage States for Urban roads.

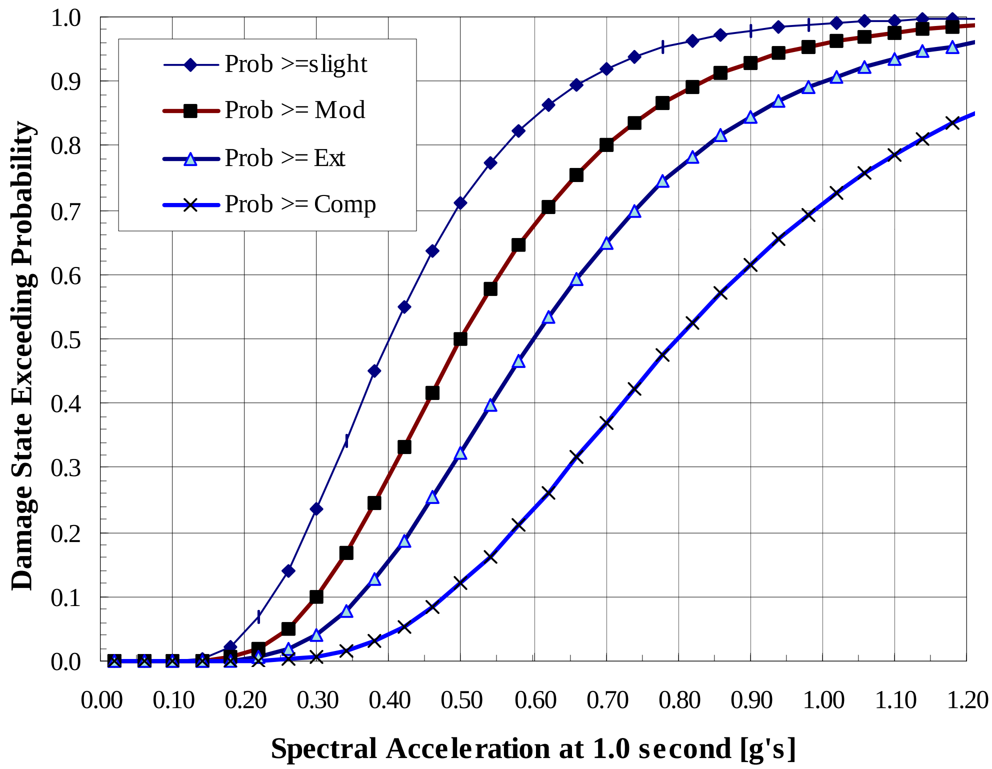


Figure 7.6 Fragility Curves for Conventially Designed Major Bridges (HWB1).

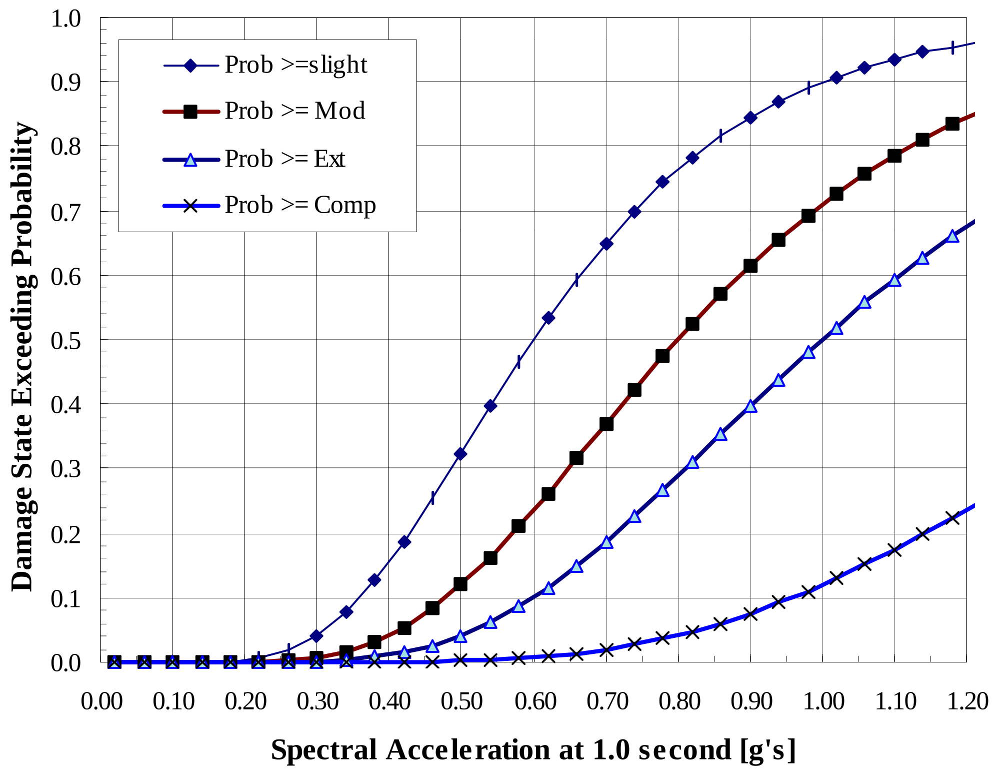


Figure 7.7 Fragility Curves for Seismically Designed Major Bridges (HWB2).

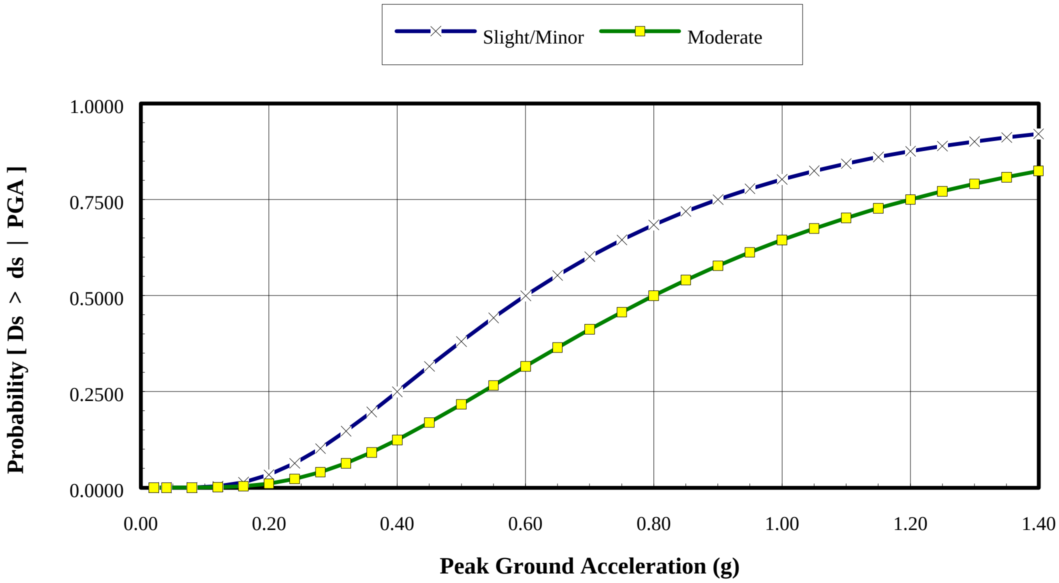


Figure 7.8 Fragility Curves at Various Damage States for Bored/Drilled Tunnels Subject to Peak Ground Acceleration.

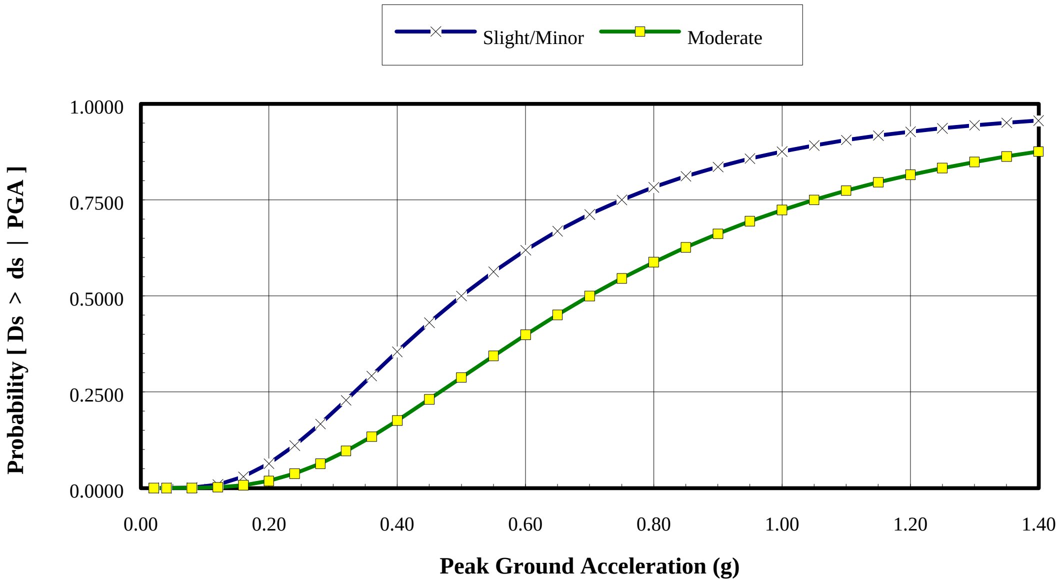


Figure 7.9 Fragility Curves at Various Damage States for Cut & Cover Tunnels Subject to Peak Ground Acceleration.

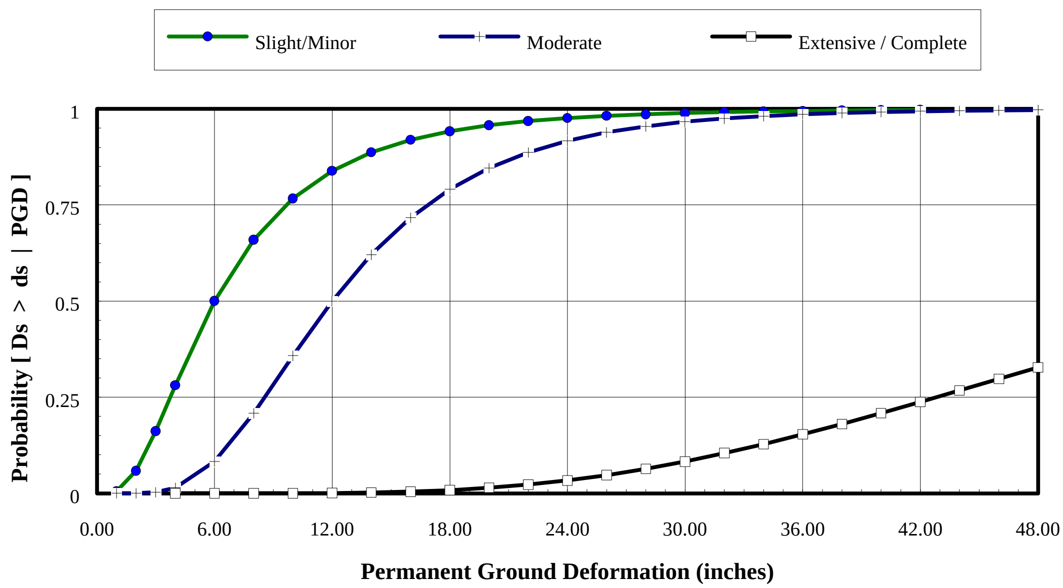


Figure 7.10 Fragility Curves at Various Damage States for All Types of Tunnels Subject to Permanent Ground deformation.

7.2 Railway Transportation System

7.2.1 Introduction

This section presents an earthquake loss estimation methodology for a railway transportation system. This system consists of tracks/roadbeds, bridges, tunnels, urban stations, maintenance facilities, fuel facilities, and dispatch facilities. Past earthquake damage reveals that bridges, tunnels, urban stations, maintenance facilities, fuel facilities, and dispatch facilities are vulnerable to both ground shaking and ground failure, while railway tracks/roadbeds are significantly affected by ground failure alone. Railway tracks located on soft soil or fill or which cross a surface fault rupture can experience failure resulting in loss of functionality. Railway bridges that fail usually result in significant disruption to the transportation network, especially bridges that cross waterways. Likewise, railway tunnels are often not redundant, and major disruption to the transportation system is likely to occur should a tunnel become non-functional.

7.2.2 Scope

The scope of this section includes development of methods for estimation of earthquake damage to a railway transportation system given knowledge of the system's components (i.e., tracks, bridges, tunnels, stations, maintenance facilities, fuel facilities, or dispatch facilities), the classification of each component (e.g., for fuel facilities, whether the equipment within the facility is anchored or not), and the ground motion (i.e. peak ground acceleration and permanent ground deformation).

Damage states describing the level of damage to each railway system component are defined (i.e. slight/minor, moderate, extensive or complete). Damage states are related to damage ratio (defined as ratio of repair to replacement cost) for evaluation of direct economic loss. Component restoration curves are provided for each damage state to evaluate loss of function. Restoration curves describe the fraction or percentage of the component that is expected to be open or operational as a function of time following the earthquake. For example, an extensively damaged railway facility might be closed (0% functional) immediately following the earthquake, but 100% functional after 30 days.

Fragility curves are developed for each type of railway system component. These curves describe the probability of reaching or exceeding each damage state given the level of ground motion.

Evaluation of component functionality is done similar to the way it was done for highway components.

Interdependence of components on the overall system functionality is not addressed by the methodology. Such considerations require a system (network) analysis.

7.2.3 Input Requirements and Output Information

Required input to estimate damage to railway systems includes the following items:

Track and Roadbeds

- Geographical location of railway links [longitude and latitude of end nodes]
- Permanent ground deformation (PGD) at trackbed link

Railway Bridges

- Geographical location of bridge (longitude and latitude)
- Peak ground acceleration (PGA) and PGD at bridge
- Bridge classification

Railway Tunnels

- Geographical location of tunnels (longitude and latitude)
- PGA and PGD at tunnel
- Tunnel classification

Railway System Facilities

- Geographical location of facilities (longitude and latitude)
- PGA and PGD at facility
- Facility classification

Direct damage output for railway systems includes probability estimates of (1) component functionality and (2) physical damage, expressed in terms of the component's damage ratio. Damage ratios, used as inputs to the direct economic loss module, are presented in section 15.3 of Chapter 15.

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

7.2.4 Form of Damage Functions

Damage functions or fragility curves for all railway system components described below are modeled as lognormal functions that give the probability of reaching or exceeding different levels of damage for a given level of ground motion. Each fragility curve is characterized by a median value of ground motion (or failure) and an associated dispersion factor (lognormal standard deviation). Ground motion is quantified in terms of peak ground acceleration (PGA) and ground failure is quantified in terms of permanent ground displacement (PGD).

- For tracks/roadbeds, fragility curves are defined in terms of PGD.
- For bridges, fragility curves are defined in terms of PGA and PGD.
- 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 and PGD.

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

7.2.5 Description of Railway System Components

A railway system consists of four components: tracks/roadbeds, bridges, tunnels, and facilities. This section provides a brief description of each.

Tracks/Roadbeds

Tracks/roadbeds refers to the assembly of rails, ties, and fastenings, and the ground on which they rest. Only one classification is adopted for these components. This classification is analogous to that of urban roads in highway systems.

Bridges

Railway bridges are classified as either seismically designed or conventionally designed. These two classifications are analogous to those for bridges in highway systems.

Tunnels

Railway tunnels follow the same classification as highway tunnels. That is, they are classified either as bored/drilled tunnels, or cut & cover tunnels.

Railway System Facilities

Railway system facilities include urban and suburban stations, maintenance facilities, fuel facilities, and dispatch facilities.

Urban and Suburban stations: are generally key connecting hubs that are important for system functionality. In western US, these buildings are mostly made of reinforced concrete shear walls or moment resisting steel frames, while in the eastern US, the small stations are mostly wood and the large ones are mostly masonry or braced steel frames..

Maintenance facilities are housed in large structures that are not usually critical for system functionality as maintenance activities can be delayed or performed elsewhere. These building structures are often made of steel braced frames.

Fuel facilities include buildings, tanks (anchored, unanchored, or buried), backup power systems (if available, anchored or unanchored diesel generators), pumps, and other equipment (anchored or unanchored). It should be mentioned that anchored equipment in general refers to equipment designed with special seismic tiedowns or tiebacks, while unanchored equipment refers to equipment designed with no special considerations other than the manufacturer's normal requirements. While some vibrating components, such as pumps, are bolted down regardless of concern for earthquakes, as used here “anchored” means all components have been engineered to meet seismic criteria which may include bracing (e.g., pipe or stack bracing) or flexibility requirements (e.g., flexible connections across separation joints) as well as anchorage. These definitions of anchored and unanchored apply to all lifeline components. The fuel facility functionality is determined with a fault tree analysis considering redundancies and subcomponent behavior. Note that generic building damage functions are used in this fault tree analysis for developing the overall fragility curve of fuel facilities. Above ground tanks are typically made of steel with roofs also made of steel. Buried tanks are typically concrete wall construction with concrete roofs. In total, five types of fuel facilities are considered. These are: fuel facilities with or without anchored equipment and with or without backup power (all combinations), and fuel facilities with buried tanks.

Dispatch facilities consist of buildings, backup power supplies (if available, anchored or unanchored diesel generators), and electrical equipment (anchored or unanchored). Generic reinforced concrete building with shear walls damage functions, are used in this fault tree analysis for developing the overall fragility curves for dispatch facilities. In total, four types of dispatch facilities are considered. These are dispatch facilities with or without anchored equipment and with or without backup power (all combinations).

7.2.6 Definitions of Damage States

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

Slight/Minor Damage (ds_2)

- For tracks and roadbeds, ds_2 is defined by minor (localized) derailment due to slight differential settlement of embankment or offset of the ground.

- For railway bridges, ds_2 is defined similar to highway bridges.

- For railway tunnels, ds_2 is defined similar to highway tunnels.

- For railway system facilities,

  ◊ for urban stations and maintenance facilities, ds_2 is defined by slight building damage (check building module for full description of potential damage).

  ◊ for fuel facilities with anchored equipment, ds_2 is defined by slight damage to pump building, minor damage to anchor of tanks, or loss of off-site power (check electric power systems for more on this) for a very short period and minor damage to backup power (i.e. to diesel generators, if available).

  ◊ for fuel facilities with unanchored equipment, ds_2 is defined by elephant foot buckling of tanks with no leakage or loss of contents, slight damage to pump building, or loss of commercial power for a very short period and minor damage to backup power (i.e to diesel generators, if available).

  ◊ for fuel facilities with buried tanks (PGD related damage), ds_2 is defined by minor uplift (few inches) of the buried tanks or minor cracking of concrete walls.

  ◊ for dispatch facilities with anchored equipment, ds_2 is defined by minor anchor damage, slight damage to building, or loss of commercial power for a very short period and minor damage to backup power (i.e. diesel generators, if available).

  ◊ for dispatch facilities with unanchored equipment, ds_2 is defined by loss of off-site power for a very short period and minor damage to backup power (i.e. to diesel generators, if available), or slight damage to building.

Moderate Damage (ds_3)

- For railway tracks and roadbeds, ds_3 is defined by considerable derailment due to differential settlement or offset of the ground. Rail repair is required.

- For railway bridges, ds_3 is defined as for highway bridges.

- For railway tunnels, ds_3 is defined as for highway tunnels

- For railway system facilities,

  ◊ for urban stations and maintenance facilities, ds_3 is defined by moderate building damage (check building module for description of potential damage).

  ◊ for fuel facilities with anchored equipment, ds_3 is defined by elephant foot buckling of tanks with no leakage or loss of contents, considerable damage to equipment, moderate damage to pump building, or loss of commercial power for few days and malfunction of backup power (i.e., diesel generators, if available).

◊ for fuel facilities with unanchored equipment, ds_3 is defined by elephant foot buckling of tanks with partial loss of contents, moderate damage to pump building, loss of commercial power for few days and malfunction of backup power (i.e., diesel generators, if available).

◊ for fuel facilities with buried tanks, ds_3 is defined by damage to roof supporting columns, and considerable cracking of walls.

◊ for dispatch facilities with anchored equipment, ds_3 is defined by considerable anchor damage, moderate damage to building, or loss of commercial power for few days and malfunction of backup power (i.e., diesel generators, if available).

◊ for dispatch facilities with unanchored equipment, ds_3 is defined by moderate damage to building, or loss of off-site power for few days and malfunction of backup power (i.e., diesel generators, if available)..

Extensive Damage (ds_4)

- For railway tracks/roadbeds, ds_4 is defined by major differential settlement of the ground resulting in potential derailment over extended length.

- For railway bridges, ds_4 is defined as for highway bridges.

- For railway tunnels, ds_4 is defined as for highway tunnels.

- For railway system facilities,

◊ for urban stations and maintenance facilities, ds_4 is defined by extensive building damage (check building module for description of potential damage).

◊ for fuel facilities with anchored equipment, ds_4 is defined by elephant foot buckling of tanks with loss of contents, extensive damage to pumps (cracked/sheared shafts), or extensive damage to pump building.

◊ for fuel facilities with unanchored equipment, ds_4 is defined by weld failure at base of tank with loss of contents, extensive damage to pump building, or extensive damage to pumps (cracked/sheared shafts).

◊ for fuel facilities with buried tanks, ds_4 is defined by considerable uplift (more than a foot) of the tanks and rupture of the attached piping.

◊ For dispatch facilities with unanchored or anchored equipment, ds_4 is defined by extensive building damage.

<u>Complete Damage</u> (ds_5)

- <u>For railway tracks/roadbeds</u>, ds_5 is the same as ds_4.

- <u>For railway bridges</u>, ds_5 is defined as for highway bridges.

- <u>For railway tunnels</u>, ds_5 is defined as for highway tunnels.

- <u>For railway system facilities</u>,

◊ For urban stations and maintenance facilities, ds_5 is defined by extensive to complete building damage (check building module for description of potential damage).

◊ For fuel facilities with anchored equipment, ds_5 is defined by weld failure at base of tank with loss of contents, or extensive to complete damage to pump building.

◊ For fuel facilities with unanchored equipment, ds_5 is defined by tearing of tank wall or implosion of tank (with total loss of content), or extensive/complete damage to pump building.

◊ For fuel facilities with buried tanks, ds_5 is same as ds_4.

◊ For dispatch facilities with unanchored or anchored equipment, ds_5 is defined by complete damage to building.

7.2.7 Component Restoration Curves

Restoration curves are developed based in part on ATC-13 damage data for the social function classifications of interest (SF 26a through SF 26d) consistent with damage states defined in the previous section. Normally distributed functions are used to approximate these restoration curves, as was done for highway systems. Means and dispersions (standard deviations) of these restoration functions are given in Table 7.10.a. Table 7.10.b gives approximate discrete functions for these developed restoration functions. Figures 7.11 through 7.14 show restoration functions for railway tracks/roadbed, bridges, tunnels and facilities, respectively. ATC-13 restoration data for railway terminal stations are used to generically represent all other railway facilities.

Table 7.10.a Continuous Restoration Functions for Railway System Components (after ATC-13, 1985)

Classification	Damage State	**Mean** (Days)	σ (days)
Railway Tracks	slight/minor	0.9	0.07
	moderate	3.3	3.0
	extensive	15.0	13.0
	complete	65.0	45.0
Railway Bridges	slight/minor	0.9	0.06
	moderate	2.8	1.8
	extensive	31.0	22.0
	complete	110.0	73.0
Railway Tunnels	slight/minor	0.9	0.05
	moderate	4.0	3.0
	extensive	37.0	30.0
	complete	150.0	80.0
Railway Facilities	slight/minor	0.9	0.05
	moderate	1.5	1.5
	extensive	15.0	15.0
	complete	65.0	50.0

Table 7.10.b Discretized Restoration Functions for Railway System Components

Classification	Damage State	1 day	3 days	7 days	30 days	90 days
		Functional Percentage				
Railway Tracks	slight/minor	90	100	100	100	100
	moderate	22	46	90	100	100
	extensive	14	18	28	87	100
	complete	6	8	10	22	70
Railway Bridges	slight/minor	80	100	100	100	100
	moderate	15	55	100	100	100
	extensive	9	10	14	50	100
	complete	7	7	8	14	40
Railway Tunnels	slight/minor	95	100	100	100	100
	moderate	16	38	85	100	100
	extensive	11	13	16	40	97
	complete	3	4	4	7	22
Railway Facilities	slight/minor	95	100	100	100	100
	moderate	37	85	100	100	100
	extensive	15	20	29	83	100
	complete	10	11	12	25	70

7.2.8 Development of Damage Functions

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

Damage functions for Railway Tracks/Roadbeds

Damage functions for tracks/roadbeds are similar to those of major roads. The medians and dispersions of these curves were given in Table 7.6 (see highway system section).

Damage Functions for Railway Bridges

Fragility curves for the two types of bridges considered herein (seismically designed and conventionally designed) are developed based on the type of damage incurred by the bridge subcomponents. Railway bridges built prior to 1960 should be classified as conventionally designed, while the rest should be classified as seismically designed. Bridge subcomponents include structural elements or portions of the bridge, such as columns, abutments, decks, approaches and connections. Medians and dispersions of damage functions to these subcomponents are summarized in Tables B.7.1 and B.7.2 of Appendix 7B, which correspond to seismically designed and conventionally designed bridges, respectively.

Component fragility curves for railway bridges are based on the probabilistic combination of subcomponent damage functions using Boolean expressions to describe the relationship between subcomponents. A lognormal curve that best fits the resulting probability distribution is then determined numerically.

A total of sixteen bridge damage functions are obtained, eight are related to PGA while the other eight are PGD related. Half of these damage functions correspond to seismically designed bridges, while the other half correspond to conventionally designed bridges. Medians and dispersions of these damage functions are given in Tables 7.11.a and 7.11.b.

Table 7.11.a Damage Algorithms for Seismically-Designed Railway Bridges

Peak Ground Acceleration			
Classification	**Damage State**	**Median (g)**	**β**
All Bridges	slight/minor	0.32	0.45
	moderate	0.62	0.55
	extensive	0.79	0.60
	complete	1.40	0.70

Permanent Ground Deformation			
Classification	**Damage State**	**Median (in)**	**β**
All Bridges	slight/minor	2.0	0.50
	moderate	9.0	0.55
	extensive	11.0	0.55
	complete	15.0	0.55

Table 7.11.b Damage Algorithms for Conventionally-Designed Railway Bridges

Peak Ground Acceleration			
Classification	**Damage State**	**Median (g)**	**β**
All Bridges	slight/minor	0.22	0.45
	moderate	0.51	0.55
	extensive	0.60	0.60
	complete	1.00	0.70

Permanent Ground Deformation			
Classification	**Damage State**	**Median (in)**	**β**
All Bridges	slight/minor	2.0	0.50
	moderate	7.0	0.55
	extensive	9.0	0.55
	complete	12.0	0.55

Graphical representations of these damage functions are also provided. Figures 7.15 and 7.16 represent PGA related fragility curves, while Figures 7.17 and 7.18 correspond to PGD related fragility curves.

Damage Functions for Tunnels

Tunnel damage functions are the same as those derived for highways. These were given in Table 7.9 and plotted in Figures 7.9 and 7.10 of the "highway systems" section.

Damage Functions for Railway System Facilities

Damage functions for railway system facilities are defined in terms of PGA and PGD. Note that, unless it is specified otherwise, ground failure (PGD) related damage functions for these facilities are assumed to be similar to those described for buildings. These are:

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

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

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

An example of how to combine multiple PGD algorithms with a PGA algorithm is presented later in this section.

PGA Damage Functions for Urban Stations and Maintenance Facilities

PGA related damage functions presented in Table 7.12.a are based on the building fragility curves developed in Chapter 5. Note that Table 7.12.a may contain more classes for urban stations or maintenance facilities than there actually are in a given system. Since no default inventory exists for both these two components, the user is expected to specify the appropriate mapping between these facilities and their actual model building types.

Table 7.12.a Damage Algorithms for Urban Stations and Maintenance Facilities

Peak Ground Acceleration					
		Map Area 7	Map Areas 5/6	Map Areas 1-4	For All Areas
Classification	**Damage State**	**Median (in)**	**Median (in)**	**Median (in)**	**β**
RC Shear Wall - low rise (C2L)	slight/minor	0.26	0.19	0.14	0.65
	moderate	0.49	0.35	0.23	0.65
	extensive	0.95	0.69	0.41	0.65
	complete	1.54	1.12	0.64	0.65
Steel Braced Frame - low rise (S2L)	slight/minor	0.24	0.18	0.12	0.65
	moderate	0.48	0.33	0.22	0.65
	extensive	1.05	0.77	0.44	0.65
	complete	1.78	1.3	0.71	0.65
Moment Resisting Steel Frame - low rise (S1L)	slight/minor	0.13	0.1	0.08	0.65
	moderate	0.33	0.23	0.16	0.65
	extensive	0.77	0.55	0.36	0.65
	complete	1.9	1.36	0.76	0.65
Steel Frame w/ URM Infill Walls - low rise (S5L)	slight/minor	0.12	0.12	0.12	0.65
	moderate	0.16	0.16	0.16	0.65
	extensive	0.29	0.29	0.29	0.65
	complete	0.46	0.46	0.46	0.65
Precast Concrete Tiltup Walls - low rise (PC1)	slight/minor	0.11	0.08	0.07	0.65
	moderate	0.25	0.17	0.11	0.65
	extensive	0.63	0.45	0.31	0.65
	complete	1.07	0.78	0.47	0.65
Concrete Frame Building w/ URM Infill Walls (C3L)	slight/minor	0.11	0.11	0.11	0.65
	moderate	0.14	0.14	0.14	0.65
	extensive	0.26	0.26	0.26	0.65
	complete	0.41	0.41	0.41	0.65
Wood, Light Frame (W1)	slight/minor	0.38	0.3	0.23	0.65
	moderate	0.69	0.49	0.36	0.65
	extensive	1.23	0.9	0.69	0.65
	complete	1.79	1.31	0.98	0.65

Damage Functions for Fuel Facilities

Fragility curves are developed for the five types of fuel facilities mentioned before, namely, fuel facilities with anchored equipment and backup power, fuel facilities with anchored equipment but no backup power, fuel facilities with unanchored equipment and backup power, fuel facilities with unanchored equipment and no backup power, and fuel facilities with buried tanks. Medians and dispersions of damage functions to fuel facility subcomponents are summarized in Tables B.7.3 and B.7.4 of Appendix 7B. A generic building type is used in developing fragility curves for fuel facilities in the specified fault tree logic (see Table B.7.3 of Appendix 7B). Note that the interaction effects, specifically that of the electric power module, are considered in this fault tree logic for the slight/minor and moderate damage states (refer to section

8.5.8 of Chapter 8 for more details on loss of commercial power effects on other lifelines).

Component fragility curves are obtained using the same methodology as used for bridges wherein a lognormal curve that best fits the results of the Boolean combination is determined numerically. It should be mentioned that the Boolean logic is implicitly presented within the definition of a particular damage state.

The fault tree shown in Figure 7.19a presents the Boolean logic for the case of moderate damage to fuel facilities with anchored equipment and backup power, while Figure 7.19b compares the fragility curve resulting from the Boolean combination to the fitted lognormal fragility curve. The dotted line in Figure 7.19 represents the overall fuel facility fragility curve.

The medians and dispersions of the damage functions for anchored and unanchored fuel facilities are shown in Table 7.12.b. These damage functions are also shown as fragility curves in Figures 7.20.a through 7.20e.

Table 7.12.b Damage Algorithms for Fuel Facilities

Peak Ground Acceleration			
Classification	**Damage State**	**Median (g)**	**β**
Facility with Anchored Components w/ Backup Power	slight/minor	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/minor	0.12	0.55
	moderate	0.27	0.50
	extensive	0.64	0.60
	complete	1.10	0.60
Facility with Unchored Components w/ Backup Power	slight/minor	0.10	0.55
	moderate	0.23	0.50
	extensive	0.48	0.60
	complete	0.80	0.60
Facility with Unchored Components w/o Backup Power	slight/minor	0.09	0.50
	moderate	0.20	0.45
	extensive	0.48	0.60
	complete	0.80	0.60

Permanent Ground Deformation			
Classification	**Damage State**	**Median (in)**	**β**
Fuel facility w/ buried tanks	slight/minor	4	0.5
	moderate	8	0.5
	extensive/ Complete	24	0.5

PGA Related Damage Functions for Dispatch Facilities

As with fuel facilities, the same generic building type is used in developing the PGA related fragility curves for dispatch facilities in the fault tree logic. The medians and dispersions of the PGA related damage functions for anchored and unanchored dispatch facilities are given in Table 7.12.c and plotted in Figures 7.21.a through 7.21.d. Note that the medians and dispersions of the damage functions for dispatch facility subcomponents are summarized in Tables B.7.5 and B.7.6 of Appendix 7B.

Table 7.12.c Damage Algorithms for Dispatch Facilities

Peak Ground Acceleration			
Classification	**Damage State**	**Median (g)**	**β**
Facility with Anchored Components w/ Backup Power	slight/minor	0.15	0.75
	moderate	0.35	0.65
	extensive	0.8	0.80
	complete	1.50	0.80
Facility with Anchored Components w/o Backup Power	slight/minor	0.12	0.50
	moderate	0.27	0.45
	extensive	0.80	0.80
	complete	1.50	0.80
Facility with Unnchored Components w/ Backup Power	slight/minor	0.13	0.55
	moderate	0.28	0.50
	extensive	0.80	0.80
	complete	1.50	0.80
Facility with Unnchored Components w/o Backup Power	slight/minor	0.11	0.45
	moderate	0.23	0.40
	extensive	0.80	0.80
	complete	1.50	0.80

Note that the values of Table 7.12c indicate that the damage functions of dispatch facilities are mostly dominated by the building behavior.

Multiple Hazards Analysis for Railway System Facilities

In this section, a hypothetical example illustrating the methodology for combining multiple hazards for nodal facilities is presented.

Assume that due to some earthquake, a railway fuel facility with anchored components and backup power is subject to a PGA level of 0.3g, a lateral spreading displacement of 12 inches, a vertical settlement of 3 inches, and a potential landslide displacement of 15 inches. Assume also that the probability of liquefaction is 0.6, and that the probability of landslide is 0.7.

- Due to ground shaking, the following probabilities of exceedence are obtained:

$$P[\, D_s \geq ds_2 \mid PGA = 0.3g \,] = 0.70$$
$$P[\, D_s \geq ds_3 \mid PGA = 0.3g \,] = 0.21$$
$$P[\, D_s \geq ds_4 \mid PGA = 0.3g \,] = 0.10$$
$$P[\, D_s \geq ds_5 \mid PGA = 0.3g \,] = 0.02$$

- Due to vertical settlement, the following probabilities of exceedence are obtained:

$$P[\, D_s \geq ds_2 \mid PGD = 3 \text{ inches} \,] = 0.16$$
$$P[\, D_s \geq ds_3 \mid PGD = 3 \text{ inches} \,] = 0.16$$
$$P[\, D_s \geq ds_4 \mid PGD = 3 \text{ inches}] = 0.16$$
$$P[\, D_s \geq ds_5 \mid PGD = 3 \text{ inches} \,] = 20\% * 0.16 = 0.03$$

- Due to lateral spreading, the following probabilities of exceedence are obtained:

$$P[\, D_s \geq ds_2 \mid PGD = 12 \text{ inches} \,] = 0.09$$
$$P[\, D_s \geq ds_3 \mid PGD = 12 \text{ inches} \,] = 0.09$$
$$P[\, D_s \geq ds_4 \mid PGD = 12 \text{ inches}] = 0.09$$
$$P[\, D_s \geq ds_5 \mid PGD = 12 \text{ inches} \,] = 20\% * 0.09 = 0.02$$

Therefore, for liquefaction, <u>vertical settlement controls</u>

- Due to landslide, the following probabilities of exceedence are obtained:

$$P[\, D_s \geq ds_2 \mid PGD = 15 \text{ inches} \,] = 0.64$$
$$P[\, D_s \geq ds_3 \mid PGD = 15 \text{ inches} \,] = 0.64$$
$$P[\, D_s \geq ds_4 \mid PGD = 15 \text{ inches}] = 0.64$$
$$P[\, D_s \geq ds_5 \mid PGD = 15 \text{ inches} \,] = 0.64$$

Next, we compute the combined probabilities of exceedence (from complete to slight/minor):

$$\begin{aligned} P[\, D_s \geq ds_5 \,] &= 0.02 + 0.6x0.03 + 0.7x0.64 \\ &\quad - 0.02x0.6x0.03 - 0.02x0.7x0.64 - 0.6x0.03x0.7x0.64 \\ &\quad + 0.02x0.6x0.03x0.7x0.64 \\ &= 0.47 \end{aligned}$$

$$\begin{aligned} P[\, D_s \geq ds_4 \,] &= 0.10 + 0.6x0.16 + 0.7x0.64 \\ &\quad - 0.10x0.6x0.16 - 0.10x0.7x0.64 - 0.6x0.16x0.7x0.64 \\ &\quad + 0.10x0.6x0.16x0.7x0.64 \\ &= 0.55 \end{aligned}$$

$$\begin{aligned} P[\, D_s \geq ds_3 \,] &= 0.21 + 0.6x0.16 + 0.7x0.64 \\ &\quad - 0.21x0.6x0.16 - 0.21x0.7x0.64 - 0.6x0.16x0.7x0.64 \\ &\quad + 0.21x0.6x0.16x0.7x0.64 \\ &= 0.61 \end{aligned}$$

$$P[\, D_s \geq ds_2 \,] = 0.70 + 0.6x0.16 + 0.7x0.64$$

$$- 0.70 \times 0.6 \times 0.16 - 0.16 \times 0.7 \times 0.64 - 0.6 \times 0.16 \times 0.7 \times 0.64$$
$$+ 0.70 \times 0.6 \times 0.16 \times 0.7 \times 0.64$$
$$= 0.85$$

Therefore, the combined discrete damage states probabilities are:

$$P[\, D_s = ds_1 \,] = 1 - 0.85 = 0.15$$
$$P[\, D_s = ds_2 \,] = 0.85 - 0.61 = 0.24$$
$$P[\, D_s = ds_3 \,] = 0.61 - 0.55 = 0.06$$
$$P[\, D_s = ds_4 \,] = 0.55 - 0.47 = 0.08$$
$$P[\, D_s = ds_5 \,] = 0.47$$

These discrete values will then be used in the evalution of functionality and economic losses.

7.2.9 Guidance for Loss Estimation Using Advanced Data and Models Analysis

For this advanced level of analysis, the expert can take advantage of the methodology's flexibility to (1) include a more refined inventory of the railway system pertaining to the area of study, and (2) include component-specific and system-specific fragility data. Default User-Supplied Data Analysis damage algorithms can be modified, or replaced, to incorporate improved information about key components of a railway system, such as urban stations. Similarly, better restoration curves can be developed, given knowledge of available resources and a more accurate layout of the railway network within the local topographic and geological conditions (i.e., if the redundancy and importance of railway components of the network are known).

7.2.10 References

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

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

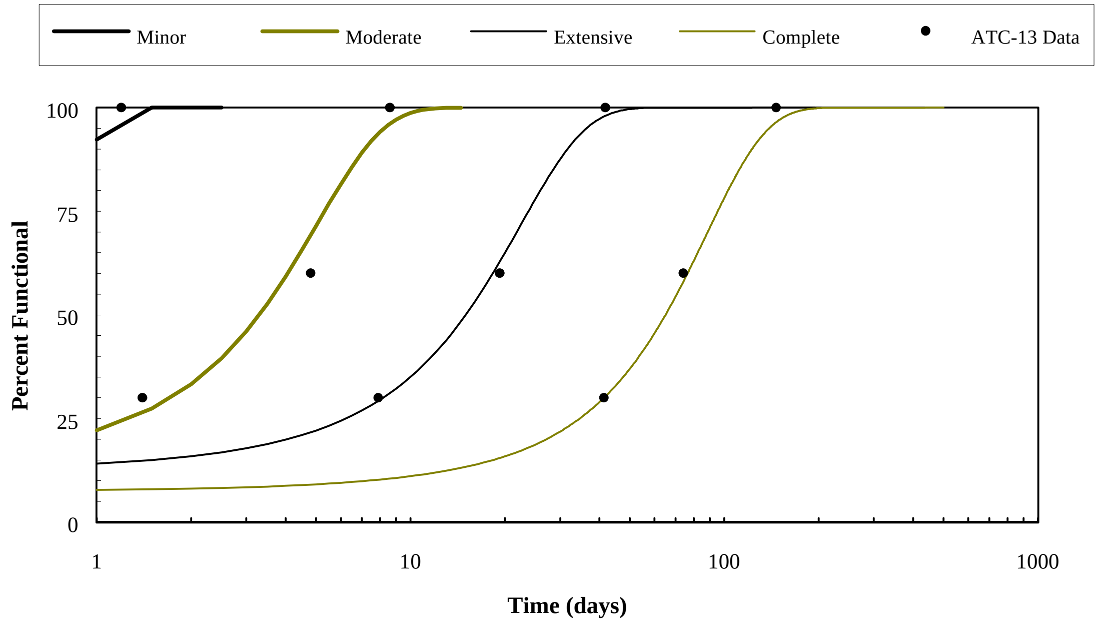


Figure 7.11 Restoration Curves for Railway Tracks/Roadbeds.

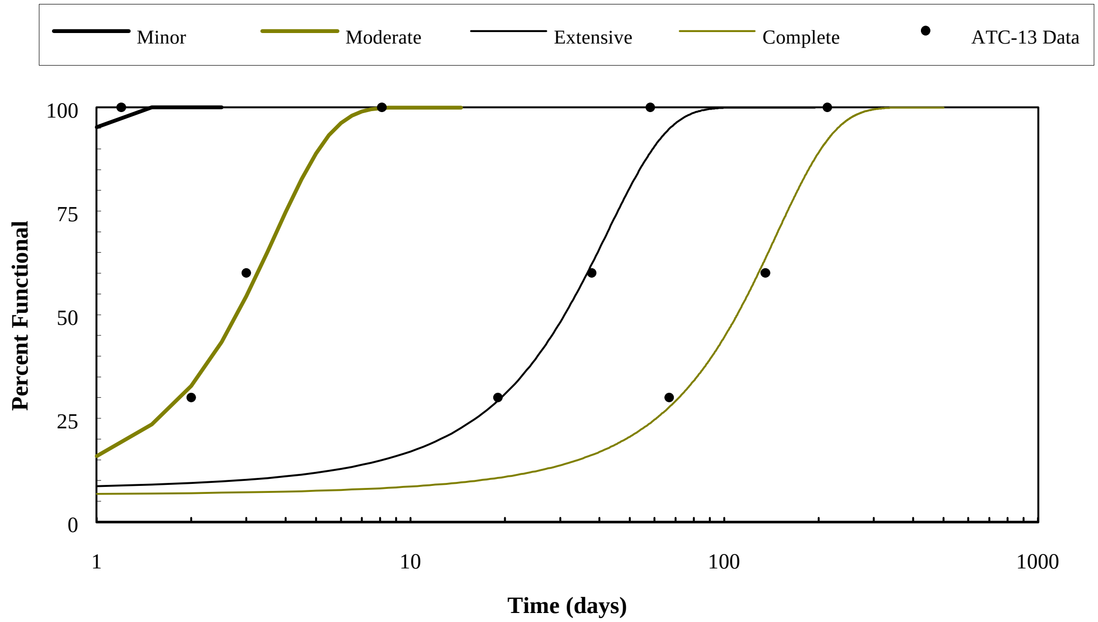


Figure 7.12 Restoration Curves for Railway Bridges.

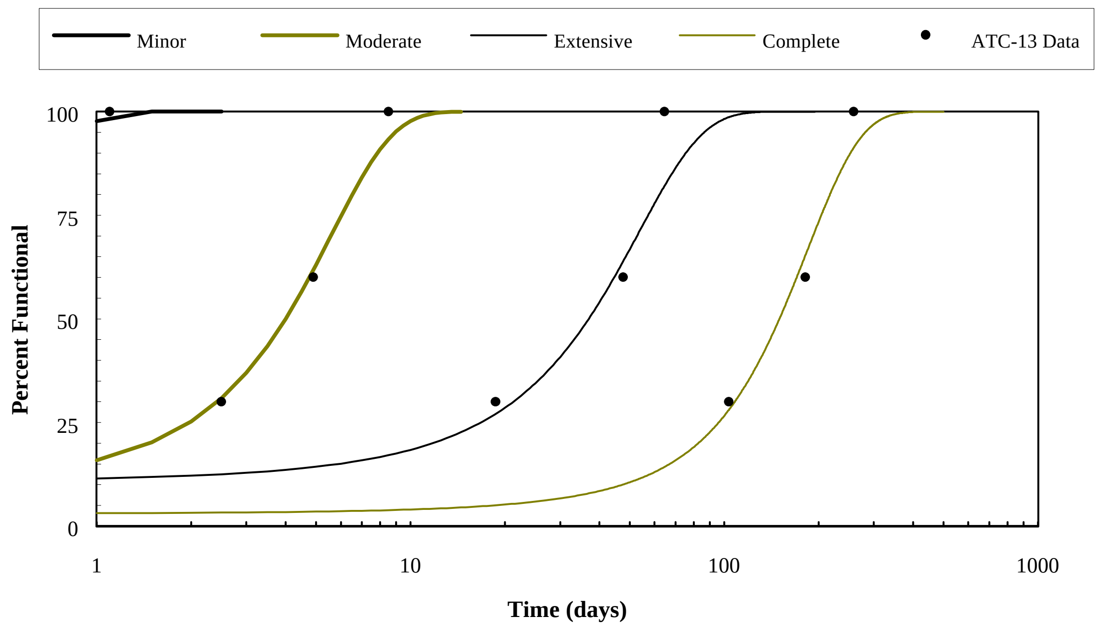


Figure 7.13 Restoration Curves for Railway Tunnels.

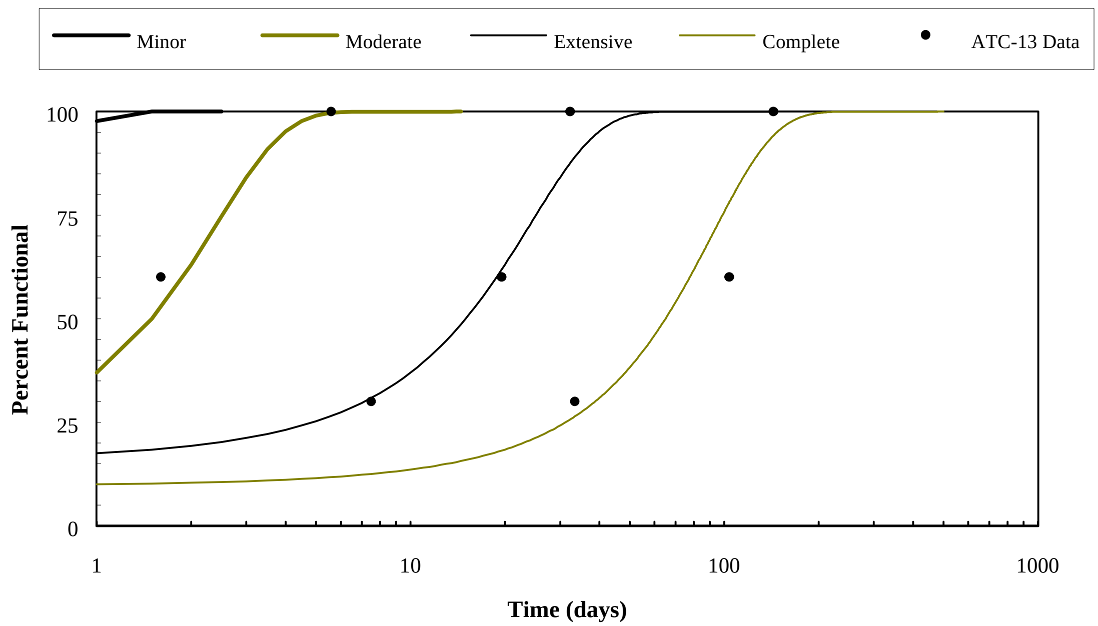


Figure 7.14 Restoration Curves for Railway Facilities.

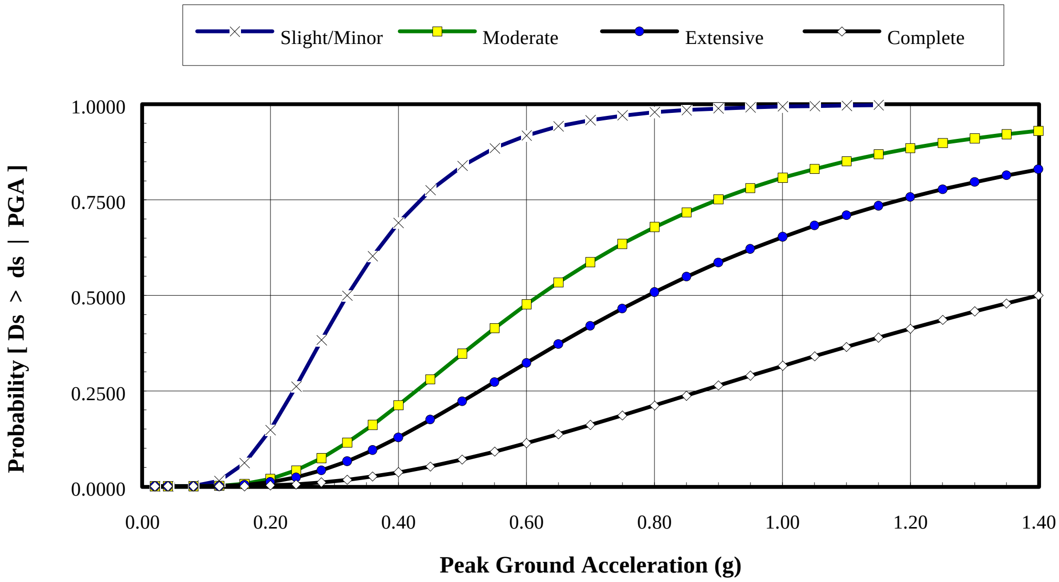


Figure 7.15 Fragility Curves at Various Damage States for Seismically Designed Railway Bridges Subject to Peak Ground Acceleration.

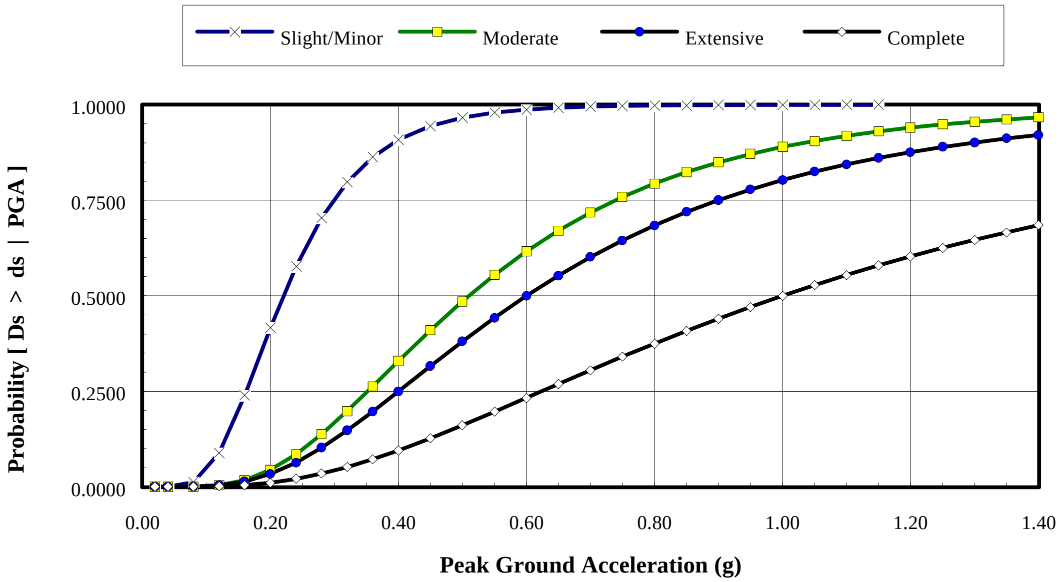


Figure 7.16 Fragility Curves at Various Damage States for Conventionally Designed Railway Bridges Subject to Peak Ground Acceleration.

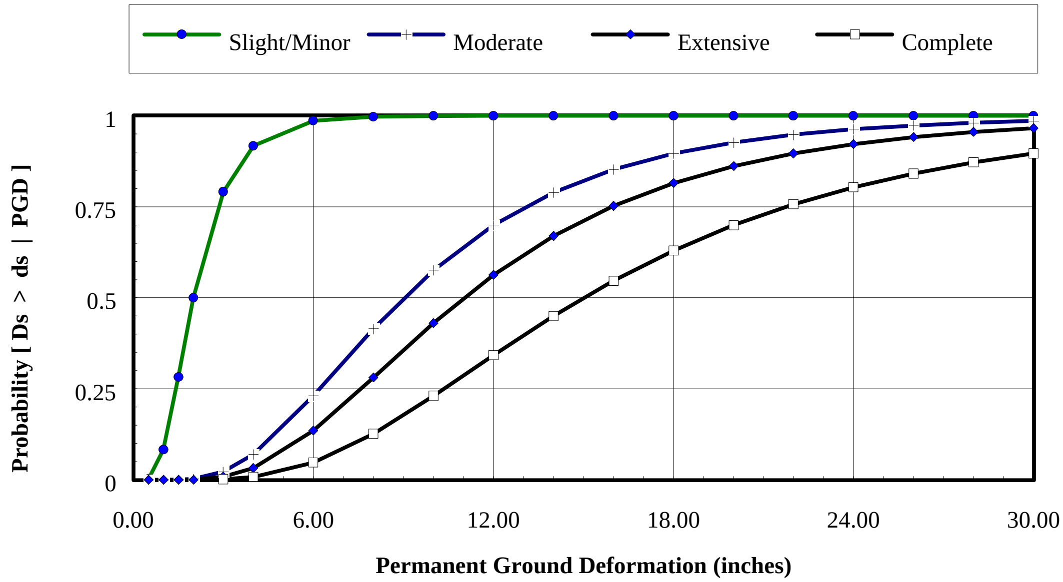


Figure 7.17 Fragility Curves at Various Damage States for Seismically-Designed Railway Bridges Subject to Permanent Ground Deformation.

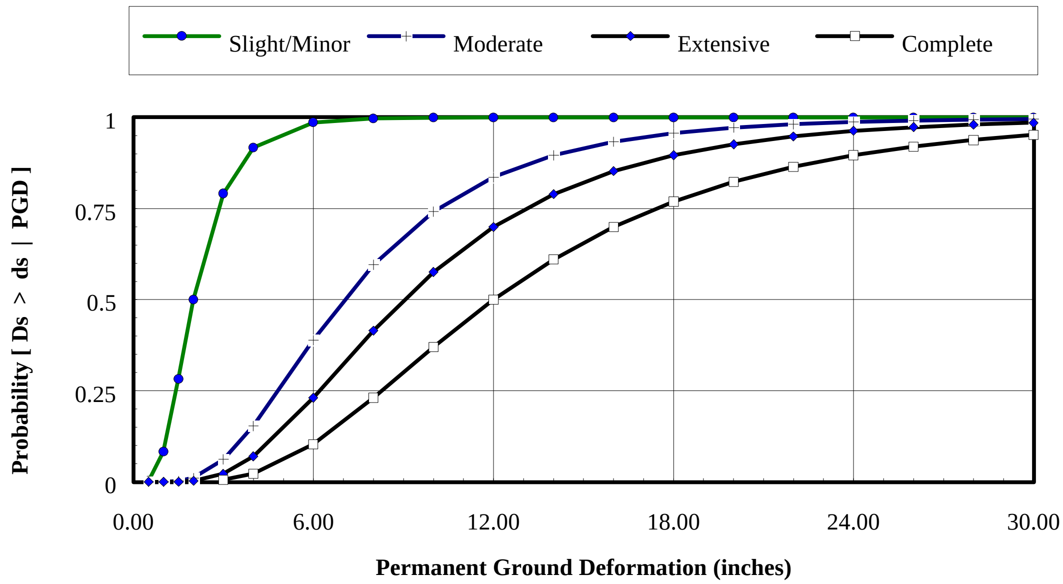


Figure 7.18 Fragility Curves at Various Damage States for Conventionally-Designed Railway Bridges Subject to PGD.

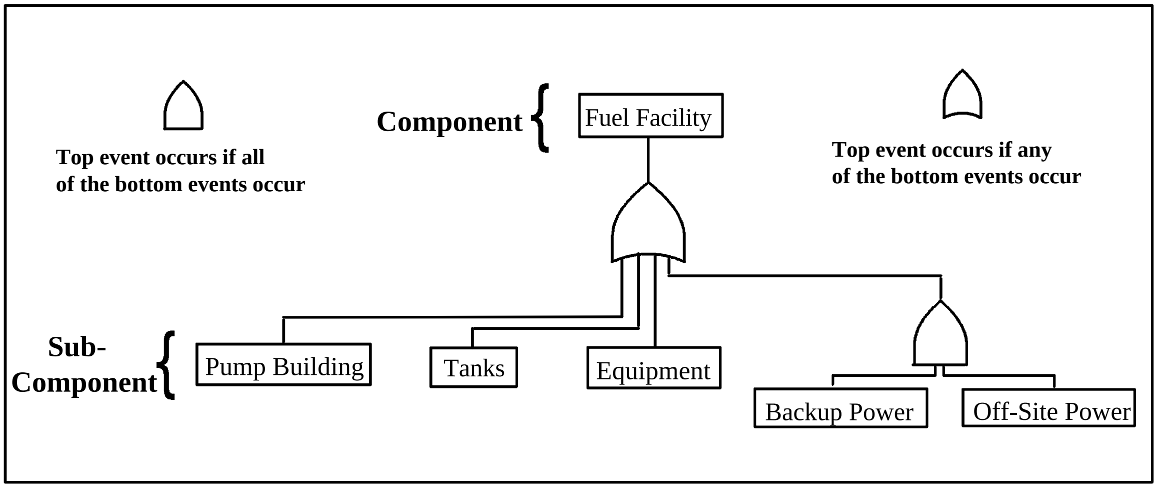


Figure 7.19a Fault Tree for Moderate Damage to Fuel Facilities with Anchored Equipment and Backup Power.

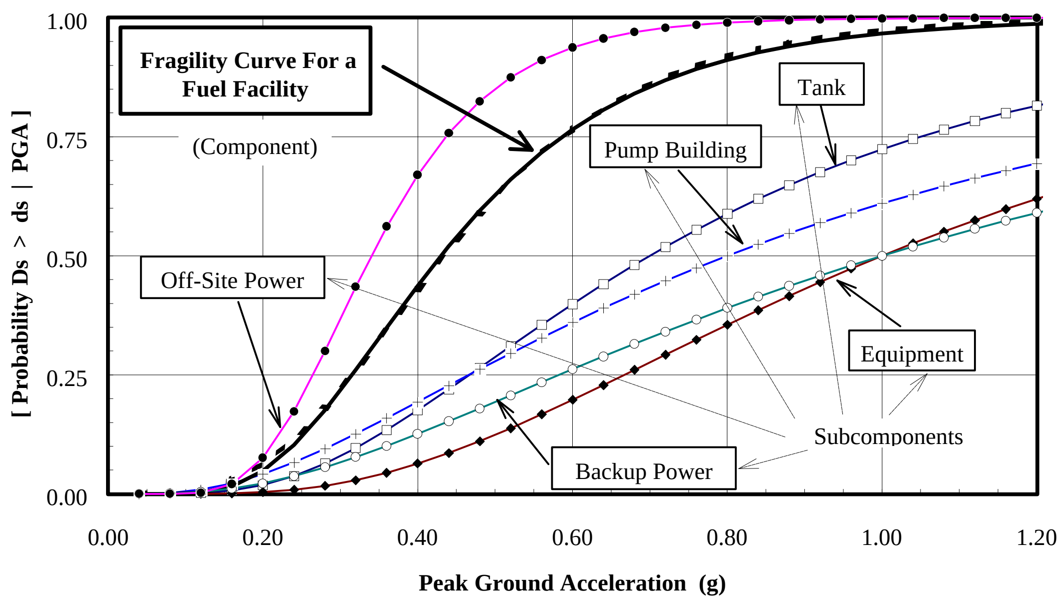


Figure 7.19b An Example of Fitting a Lognormal Curve (solid line) to a Fuel Facility Fragility Curve (dotted line).

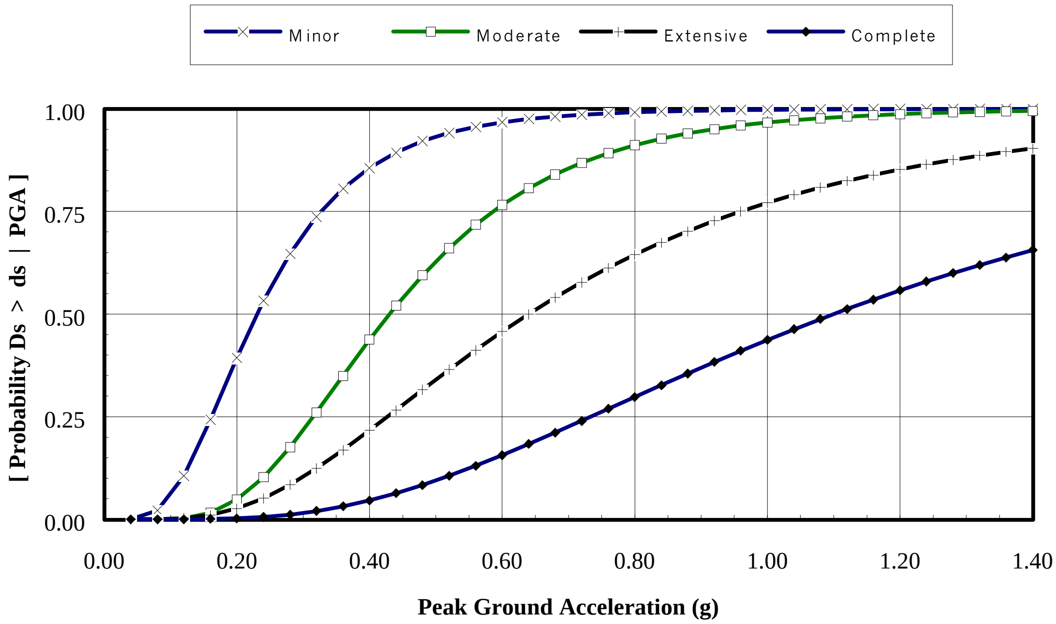


Figure 7.20.a Fragility Curves at Various Damage States for Fuel Facility with Anchored Components and Backup Power.

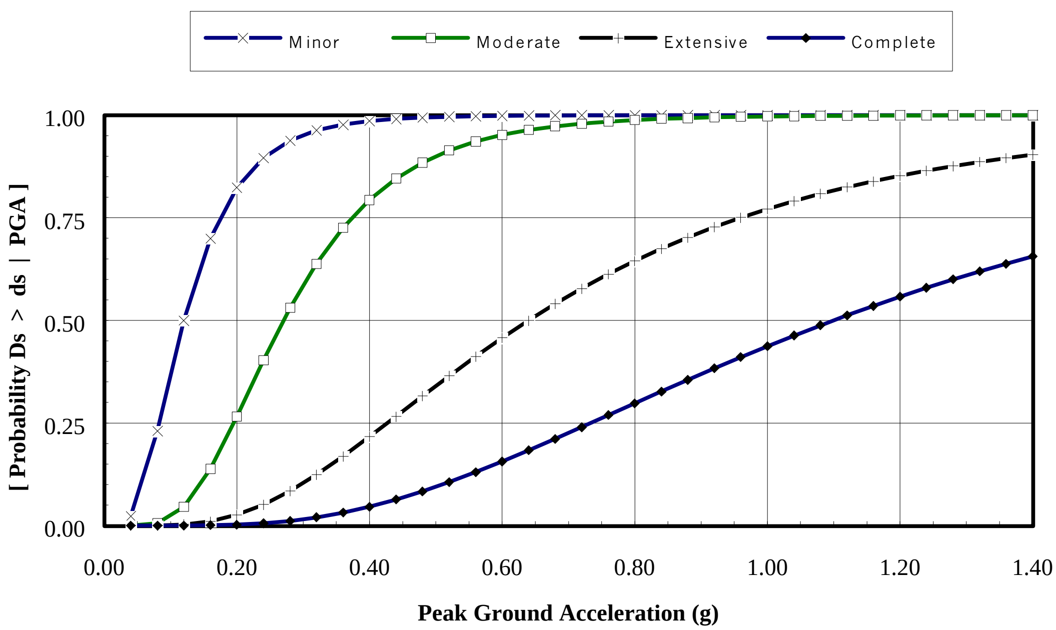


Figure 7.20.b Fragility Curves at Various Damage States for Fuel Facility with Anchored Components but no Backup Power.

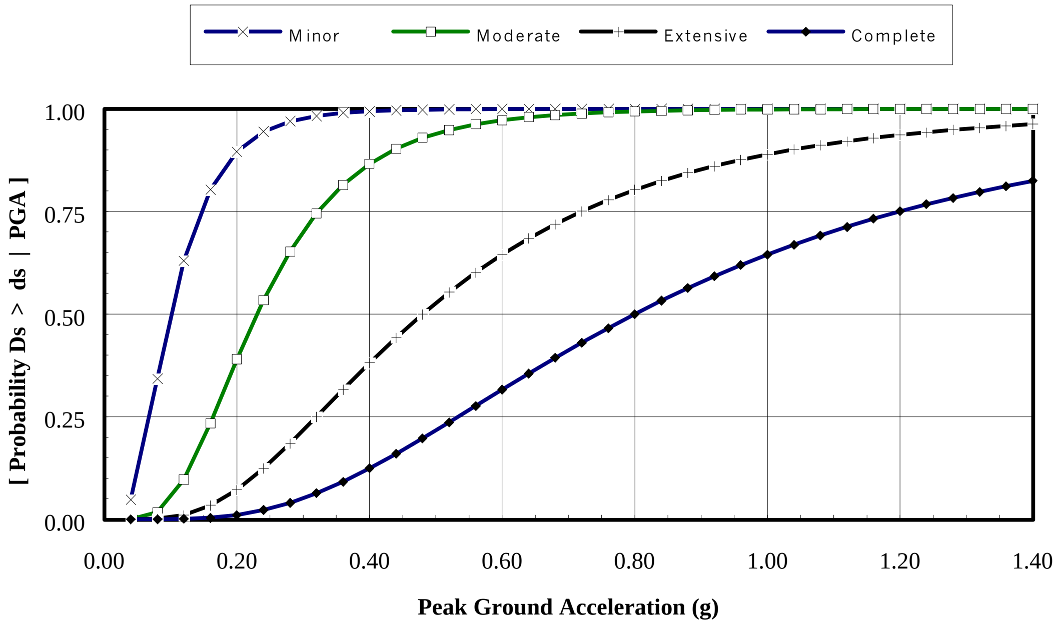


Figure 7.20.c Fragility Curves at Various Damage States for Fuel Facility with Unanchored Components and Backup Power.

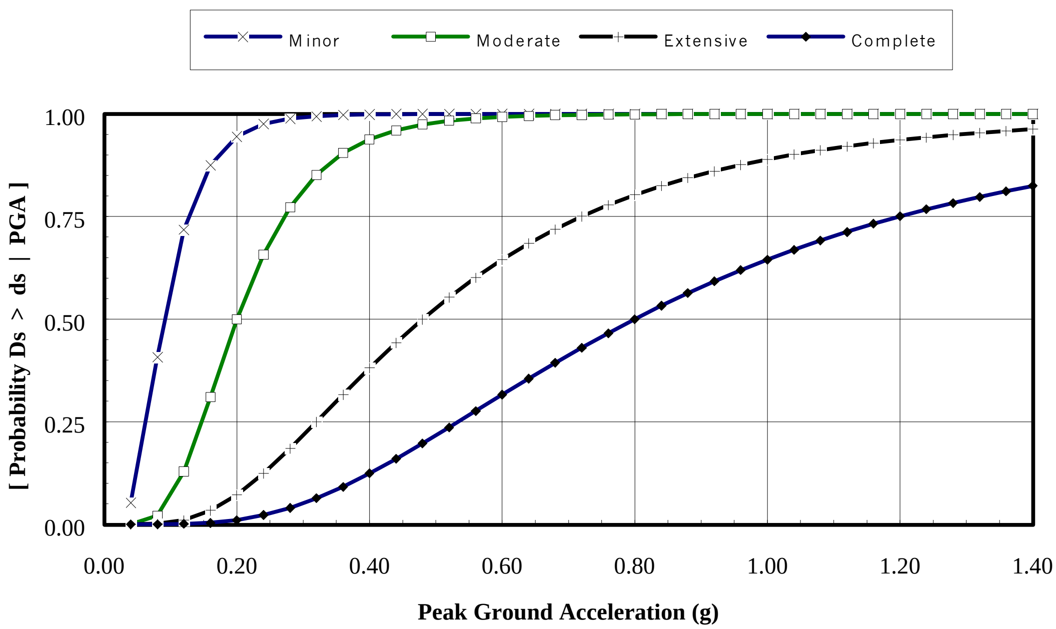


Figure 7.20.d Fragility Curves at Various Damage States for Fuel Facility with Unanchored Components and no Backup Power.

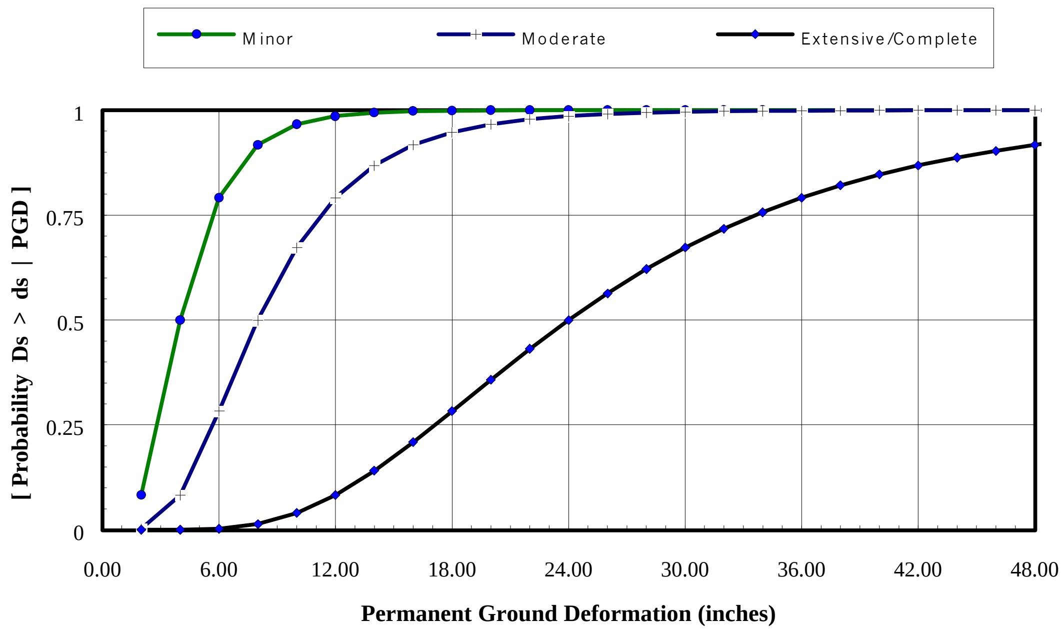


Figure 7.20.e Fragility Curves at Various Damage States for Fuel Facility with Buried Tanks Subject to Permanent Fround Deformation.

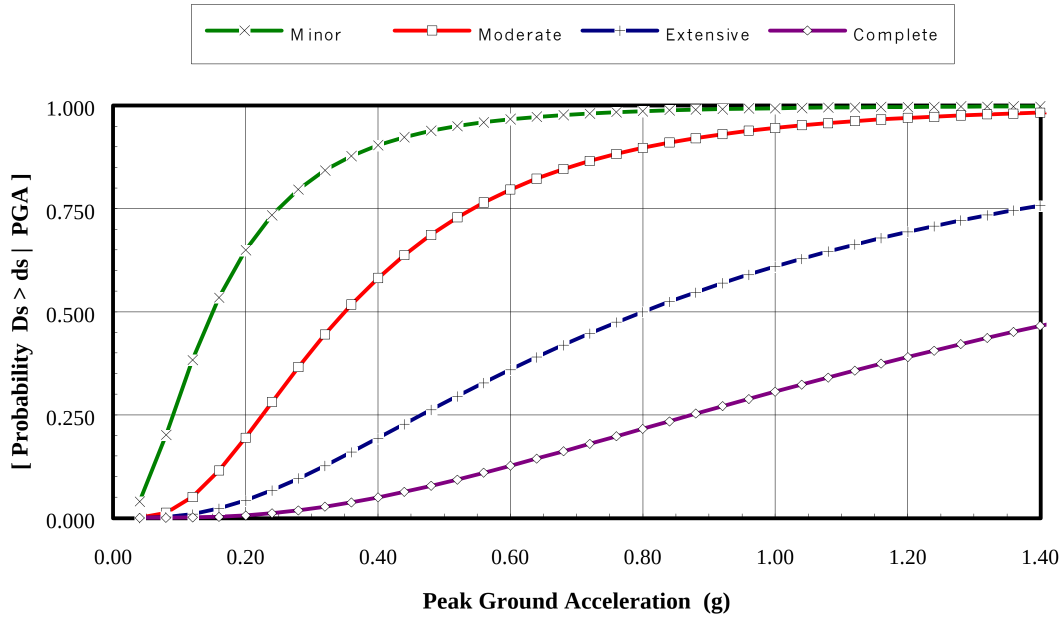


Figure 7.21.a Fragility Curves at Various Damage States for Dispatch Facility with Anchored Components and Backup Power.

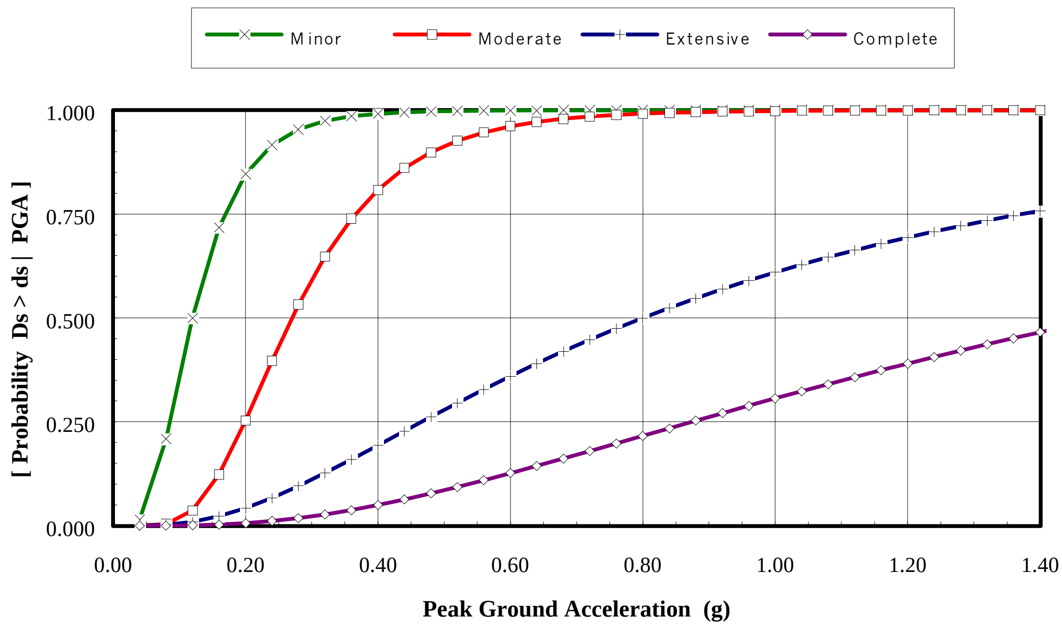


Figure 7.21.b Fragility Curves at Various Damage States for Dispatch Facility with Anchored Components but no Backup Power.

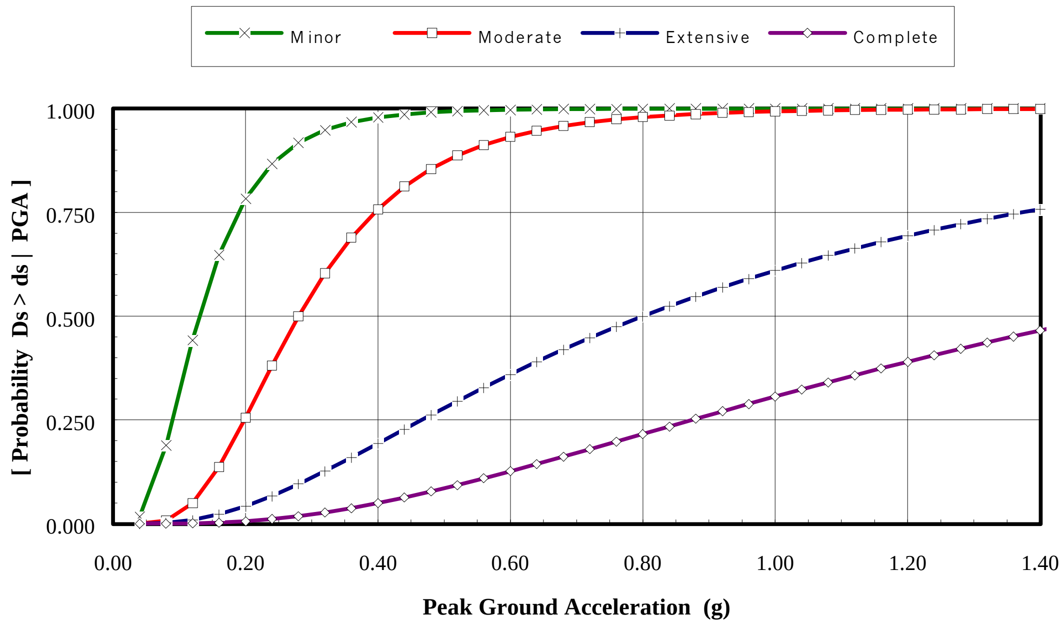


Figure 7.21.c Fragility Curves at Various Damage States for Dispatch Facility with Unanchored Components and Backup Power.

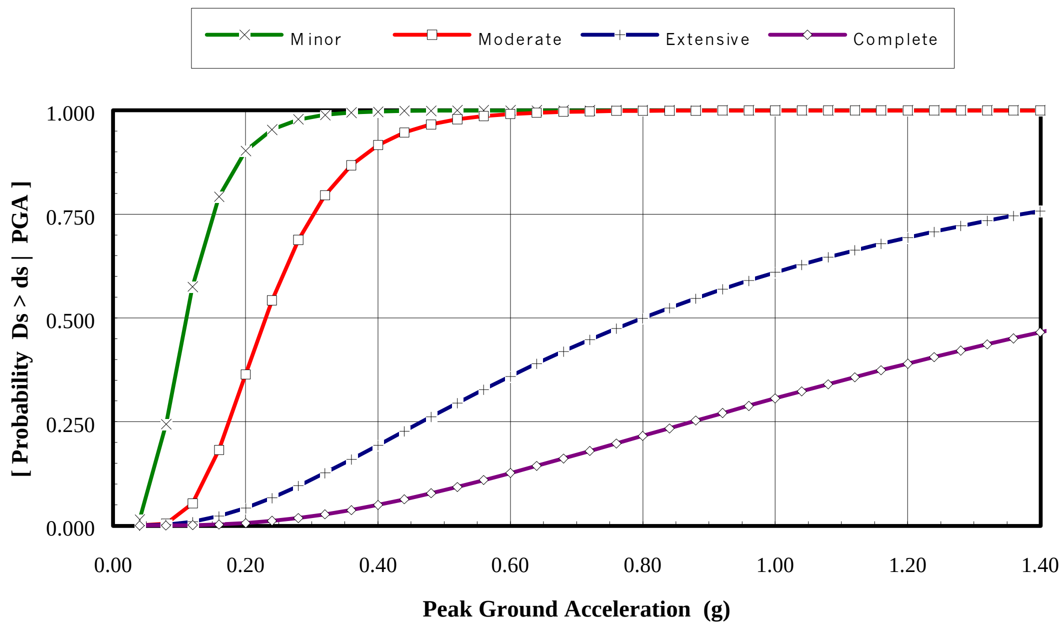


Figure 7.21.d Fragility Curves at Various Damage States for Dispatch Facility with Unanchored Components and no Backup Power.

7.3 Light Rail Transportation System

7.3.1 Introduction

This section presents an earthquake loss estimation methodology for a light rail transportation system. Like railway systems, light rail systems consist of railway tracks/roadbeds, bridges, tunnels, maintenance facilities, dispatch facilities and DC power substations. Therefore, the only difference in the case of light rail systems is in the fuel facilities, which are DC power substations.

7.3.2 Scope

The scope of this section includes development of methods for estimation of earthquake damage to a light rail transportation system given knowledge of the system's components, the classification of each component (e.g., for dispatch facilities, whether the facility's equipment is anchored or not), and the ground motion (i.e. peak ground acceleration and/or permanent ground deformation).

Damage states describing the level of damage to each light rail system component are defined (i.e. slight, moderate, extensive or complete). Damage states are related to damage ratio (defined as ratio of repair to replacement cost) for evaluation of direct economic loss. Component restoration curves are provided for each damage state to evaluate loss of function.

Fragility curves are developed for each type of light rail system component. These curves describe the probability of reaching or exceeding each damage state given the level of ground motion.

Interdependence of components on overall system functionality is not addressed by the methodology. Such considerations require a system (network) analysis that would be performed separately by a light rail system expert as an advanced study.

7.3.3 Input Requirements and Output Information

Required input to estimate damage to light rail systems includes the following items:

<u>Light Rail Tracks/Roadbeds</u>

- Geographical location of railway links [longitude and latitude of end nodes]
- Permanent ground deformation (PGD) at roadbed link

<u>Light Rail Bridges</u>

- Geographical location of bridge [longitude and latitude]
- Peak ground acceleration (PGA) and PGD at bridge

- Bridge classification

<u>Light Rail Tunnels</u>

- Geographical location of tunnels [longitude and latitude]
- PGA and PGD at tunnel
- Tunnel Classification

<u>Light Rail Facilities (DC substations, maintenance and dispatch facilities)</u>

- Geographical location of facilities [longitude and latitude]
- PGA and PGD at facility
- Classification

Direct damage output for light rail systems includes probability estimates of (1) component functionality and (2) physical damage, expressed in terms of the component's damage ratio. Note that damage ratios, which are the inputs to direct economic loss methods, are described in section 15.3 of Chapter 15.

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

7.3.4 Form of Damage Functions

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

- Fragility curves for tracks/roadbeds are the same as for railway tracks/roadbeds.
- Fragility curves for bridges are the same as for railway bridges.
- Fragility curves for tunnels are the same as for railway tunnels.
- Fragility curves for maintenance and dispatch facilities are the same as for railway maintenance and dispatch facilities.
- Fragility curves for DC power substations are defined in terms of PGA and PGD.

7.3.5 Description of Light Railway System Components

A light rail system consists mainly of six components: tracks/roadbeds, bridges, tunnels, maintenance facilities, dispatch facilities, and DC power substations. The first five are the same as for railway systems and are already described in Section 7.2. Therefore, only DC substations will be described in this subsection.

DC Power Substations

Light rail systems use electric power and have low voltage DC power substations. DC power is used by the light rail system's electrical distribution system. The DC power substations consist of electrical equipment, which convert the local electric utility AC power to DC power. Two types of DC power stations are considered. These are: (1) DC power stations with anchored (seismically designed) components and (2) DC power stations with unanchored (which are not seismically designed) components.

7.3.6 Definitions of Damage States

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

Slight or Minor Damage (ds_2)

- For tracks/roadbeds, ds_2 is defined similar to railway tracks.
- For light rail bridges, ds_2 is defined similar to railway bridges.
- For light rail tunnels, ds_2 is defined similar to highway tunnels.
- For light rail system facilities,

  ◊ For maintenance facilities, ds_2 is defined similar to railway maintenance facilities.

  ◊ For dispatch facilities, ds_2 is defined similar to railway dispatch facilities.

  ◊ For DC power substations with anchored or unanchored components, ds_2 is defined by loss of off-site power for a very short period, or slight damage to building.

Moderate Damage (ds_3)

- For tracks/roadbeds, ds_3 is defined similar to railway tracks.
- For light rail bridges, ds_3 is defined similar to railway bridges.
- For light rail tunnels, ds_3 is defined similar to highway tunnels.

- For light rail system facilities,

  ◊ For maintenance facilities, ds_3 is defined similar to railway maintenance facilities.

  ◊ For dispatch facilities, ds_3 is defined similar to railway dispatch facilities.

  ◊ For DC power substations with anchored or unanchored components, ds_3 is defined by loss of off-site power for few days, considerable damage to equipment, or moderate damage to building.

Extensive Damage (ds_4)

- For tracks/roadbeds, ds_4 is defined similar to railway tracks.
- For light rail bridges, ds_4 is defined similar to railway bridges.
- For light rail tunnels, ds_4 is defined similar to highway tunnels.
- For light rail system facilities,

  ◊ For maintenance facilities, ds_4 is defined similar to railway maintenance facilities.

  ◊ For dispatch facilities, ds_4 is defined similar to railway dispatch facilities.

  ◊ For DC power substations with anchored or unanchored components, ds_4 is defined by extensive building damage.

Complete Damage (ds_5)

- For tracks/roadbeds, ds_5 is defined similar to railway tracks.
- For light rail bridges, ds_5 is defined similar to railway bridges.
- For light rail tunnels, ds_5 is defined similar to highway tunnels.
- For light rail system facilities,

  ◊ For maintenance facilities, ds_5 is defined similar to railway maintenance facilities.

  ◊ For dispatch facilities, ds_5 is defined similar to railway dispatch facilities.

◊ For DC power substations with anchored or unanchored components, ds_5 is defined by complete building damage.

7.3.7 Component Restoration Curves

The restoration curves for light rail tracks/roadbeds, bridges, tunnels, and facilities are assumed to be the same as those for railway system components.

7.3.8 Development of Damage Functions

Fragility curves for light rail system components are defined with respect to classification and ground motion parameter. Again, except for DC power stations, damage functions of the other light rail system components have been already established in either section 7.1 (highway systems) or section 7.2 (railway systems).

Damage functions for Light Rail Tracks/Roadbeds

See damage functions for railway tracks/roadbeds.

Damage Functions for Light Rail Bridges

See damage functions for railway bridges.

Damage Functions for Light Rail Tunnels

See damage functions for highway tunnels.

Damage Functions for Light Rail System Facilities

Damage functions for light rail system facilities are defined in terms of PGA and PGD. Note that ground failure (PGD) related damage functions for these facilities are assumed to be similar to those described for railway system facilities in section 7.2.8.

PGA Related Damage Functions for Maintenance Facilities

Maintenance facilities for light rail systems are mostly made of steel braced frames. Since no default inventory is provided for these facilities, the user will be expected to provide the appropriate mapping between these facilities whose damage functions are listed in Table 7.7 of section 7.2.8 and their model building types.

PGA Related Damage Functions for Dispatch Facilities

See damage functions for railway dispatch facilities.

PGA Related Damage Functions for DC Power Substations

Fragility curves for the two types of DC power substations are developed based on the type of damage incurred by the DC power substation subcomponents (building, equipment, and off-site power for interaction effects). These two types are DC power substations with unanchored equipment, and DC power substations with unanchored equipment. Medians and dispersions of damage functions to DC power substations subcomponents are summarized in Tables C.7.1 and C.7.2 of Appendix 7C. Component fragility curves are obtained using the same methodology as used before. That is, each fragility curve is determined by a lognormal curve that best fits the results of the Boolean combination. It should be mentioned that the Boolean logic is implicitly presented within the definition of a particular damage state. The medians and dispersions of the damage functions for anchored and unanchored DC power substations are shown in Table 7.13 and plotted in Figures 7.22.a and 7.22.b.

Table 7.13 Damage Algorithms for DC Power Substations

Peak Ground Acceleration			
Classification	**Damage State**	**Median (g)**	**β**
Substation with Anchored Components	slight moderate extensive complete	0.12 0.27 0.80 1.50	0.55 0.45 0.80 0.80
Substation with Unnchored Components	slight moderate extensive complete	0.11 0.23 0.80 1.50	0.50 0.40 0.80 0.80

7.3.9 Guidance for Loss Estimation Using Advanced Data and Models Analysis

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

7.3.10 References

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

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

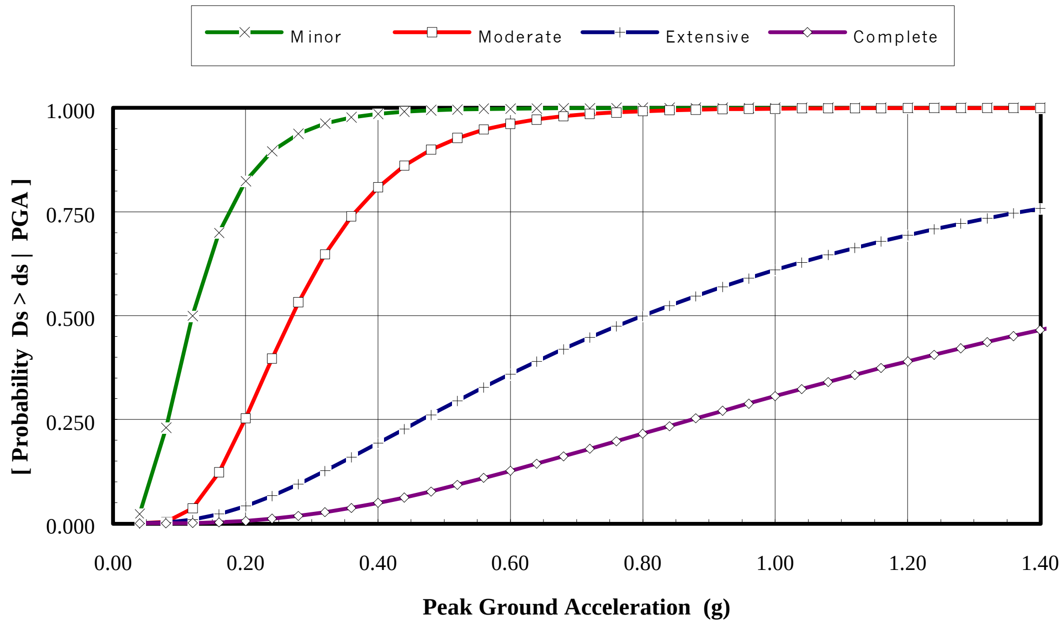


Figure 7.22.a Fragility Curves at Various Damage States for DC Power Substations with Anchored Components.

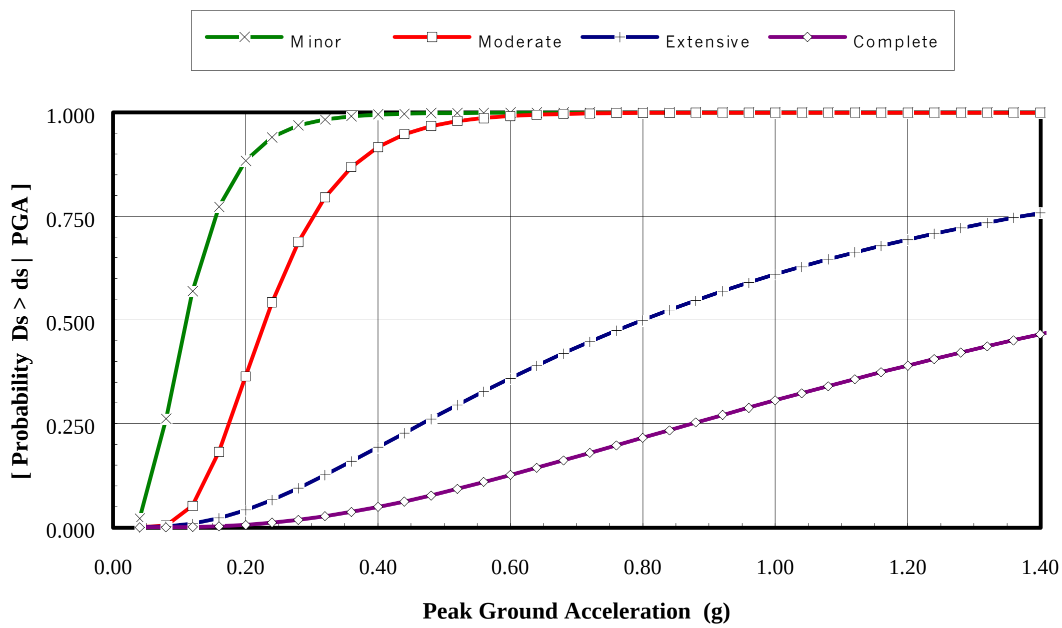


Figure 7.22.b Fragility Curves at Various Damage States for DC Power Substations with Unanchored Components.

7.4 Bus Transportation System

7.4.1 Introduction

This section presents a loss estimation methodology for a bus transportation system during earthquakes. Bus facilities consist of maintenance, fuel, and dispatch facilities. The facilities may sustain damage due to ground shaking or ground failure. Major losses can occur if bus maintenance buildings collapse, and operational problems may arise if a dispatch facility is damaged.

7.4.2 Scope

The scope of this section includes development of methods for estimation of earthquake damage to a bus transportation system given knowledge of components (i.e., fuel, maintenance, and dispatch facilities with or without backup power), classification (i.e. for fuel facilities, anchored or unanchored components), and the ground motion (i.e. peak ground acceleration and/or permanent ground deformation).

Damage states describing the level of damage to each of the bus system components are defined (i.e. slight, moderate, extensive or complete). Damage states are related to damage ratio (defined as ratio of repair to replacement cost) for evaluation of direct economic loss. Component restoration curves are provided for each damage state to evaluate loss of function. Restoration curves describe the fraction or percentage of the component that is expected to be open or operational as a function of time following the earthquake. For bus systems, the restoration is dependent upon the extent of damage to the fuel, maintenance, and dispatch facilities.

Fragility curves are developed for each class of bus system component. These curves describe the probability of reaching or exceeding each damage state given the level of ground motion. Based on these fragility curves, a method for assessing functionality of each of the three bus system components is presented.

Interdependence of components on overall system functionality is not addressed by the methodology. Such considerations require a system (network) analysis that would be performed separately by a bus system expert as an advanced study.

7.4.3 Input Requirements and Output Information

Required input to estimate damage to bus systems includes the following items:

Urban Stations

- Geographical location of site
- PGA and PGD at station
- Classification

Fuel Facilities

- Geographical location of site
- PGA and PGD at facility
- Classification (i.e. with or without anchored equipment and backup power)

Maintenance Facilities

- Geographical location of site
- PGA and PGD at facility
- Classification (i.e. building type)

Dispatch Facilities

- Geographical location of each warehouse
- PGA and PGD at facility
- Classification (i.e. with or without anchored equipment and backup power)

Direct damage output for bus systems includes probability estimates of (1) component functionality and (2) physical damage, expressed in terms of the component's damage ratio.

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

7.4.4 Form of Damage Functions

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

- For urban stations, the fragility curves are defined in terms of PGA 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 PGA and PGD.

- For dispatch facilities, the fragility curves are defined in terms of PGA and PGD.

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

7.4.5 Description of Bus System Components

A bus system consists mainly of four components: urban stations, fuel facilities, maintenance facilities, and dispatch facilities. This section provides a brief description of each.

Urban Stations

These are mainly buildings structures.

Bus System Fuel Facilities

Fuel facility consists of fuel storage tanks, buildings, pump equipment and buried pipe, and, sometimes, backup power. The fuel facility functionality is determined with a fault tree analysis considering redundancies and sub-component behavior. The same classes assumed for railway fuel facilities are assumed here. These are listed in Table 3.9.

Bus System Maintenance Facilities

Maintenance facilities for bus systems are mostly made of steel braced frames. The same classes assumed for railway maintenance facilities are assumed here. These are listed in Table 3.9.

Bus System Dispatch Facilities

The same classes assumed for railway dispatch facilities are assumed here. These are listed in Table 3.9.

7.4.6 Definitions of Damage States

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

Slight Damage (ds_2)

◊ For urban stations, ds_2 is defined similar to railway urban stations.

◊ For fuel facilities, ds_2 is defined similar to railway fuel facilities.

◊ For maintenance facilities, ds_2 is defined similar to railway maintenance facilities.

◊ For dispatch facilities, ds_2 is defined similar to railway dispatch facilities.

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

◊ For urban stations, ds_3 is defined similar to railway urban stations.

◊ For fuel facilities, ds_3 is defined similar to railway fuel facilities.

◊ For maintenance facilities, ds_3 is defined similar to railway maintenance facilities.

◊ For dispatch facilities, ds_3 is defined similar to railway dispatch facilities.

<u>Extensive Damage</u> (ds_4)

◊ For urban stations, ds_4 is defined similar to railway urban stations.

◊ For fuel facilities, ds_4 is defined similar to railway fuel facilities.

◊ For maintenance facilities, ds_4 is defined similar to railway maintenance facilities.

◊ For dispatch facilities, ds_4 is defined similar to railway dispatch facilities.

<u>Complete Damage</u> (ds_5)

◊ For urban stations, ds_5 is defined similar to railway urban stations.

◊ For fuel facilities, ds_5 is defined similar to railway fuel facilities.

◊ For maintenance facilities, ds_5 is defined similar to railway maintenance facilities.

◊ For dispatch facilities, ds_5 is defined similar to railway dispatch facilities.

7.4.7 Component Restoration Curves

Restoration Curves are developed based on a best fit to ATC-13 damage data for the social functions SF 26a through SF 26d, consistent with damage states defined in the previous section. Normal distribution functions are developed using the ATC-13 data for the mean time for 30%, 60% and 100% restoration of different sub-components in different damage states. The restoration curves for bus transportation systems are similar to those of railway transportation systems. Means and dispersions of these restoration functions are given in Tables 7.10.a. Discretized restoration functions are shown in Table 7.10.b, where the percentage restoration is shown at discrete times.

7.4.8 Development of Damage Functions

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

Damage Functions for Bus System Urban Stations

Urban stations are classified based on the building structural type. Damage functions for bus system urban stations are similar to those for the railway transportation system (see Section 7.2.8).

Damage Functions for Bus System Fuel Facilities

Fuel facilities are classified based on two criteria: (1) whether the sub-components comprising the fuel facilities are anchored or unanchored and (2) whether backup power exists in the facility. Damage functions for bus system fuel facilities are similar to those for the railway transportation system (see Section 7.2.8).

Damage Functions for Bus System Maintenance Facilities

The PGA and PGD median values for the damage states of maintenance facilities are similar to those of light rail maintenance facilities presented in Section 7.3.8.

Damage Functions for Bus System Dispatch Facility

The PGA and PGD median values for the damage states of dispatch facilities are similar to those of railway dispatch facilities given in Section 7.2.8.

7.4.9 Guidance for Loss Estimation using Advanced Data and Models Analysis

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

7.4.10 References

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

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

7.5 Port Transportation System

7.5.1 Introduction

This section presents a loss estimation methodology for a port transportation system. Port facilities consist of waterfront structures (e.g., wharfs, piers and seawalls); cranes and cargo handling equipment; fuel facilities; and warehouses. In many cases, these facilities were constructed prior to widespread use of engineered fills; consequently, the wharf, pier, and seawall structures are prone to damage due to soil failures such as liquefaction. Other components may be damaged due to ground shaking as well as ground failure.

7.5.2 Scope

The scope of this section includes developing methods for estimating earthquake damage to a port transportation system given knowledge of components (i.e., waterfront structures, cranes and cargo handling equipment, fuel facilities, and warehouses), classification (i.e. for fuel facilities, anchored or unanchored components, with or without back-up power), and the ground motion (i.e. peak ground acceleration and/or permanent ground deformation).

Damage states describing the level of damage to each of the port system components are defined (i.e. slight, moderate, extensive or complete). Damage states are related to damage ratio (defined as ratio of repair to replacement cost) for evaluation of direct economic loss. Component restoration curves are provided for each damage state to evaluate loss of function. Restoration curves describe the fraction or percentage of the component that is expected to be open or operational as a function of time following the earthquake. For ports the restoration is dependent upon the extent of damage to the waterfront structures, cranes/cargo handling equipment, fuel facilities, and warehouses. From the standpoint of functionality of the port, the user should consider the restoration of only the waterfront structures and cranes since the fuel facilities and warehouses are not as critical to the functionality of the port.

Fragility curves are developed for each class of port system component. These curves describe the probability of reaching or exceeding a certain damage state given the level of ground motion. Based on these fragility curves, a method for assessing functionality of each of the four port system components is presented.

Interdependence of components on overall system functionality is not addressed by the methodology. Such considerations require a system (network) analysis that would be performed separately by a port system expert as an advanced study.

7.5.3 Input Requirements and Output Information

Required input to estimate damage to port systems includes the following items:

Waterfront Structures

- Geographic location of port (longitude and latitude)
- PGA & PGD
- Classification

Cranes/Cargo Handling Equipment

- Geographic location of port (longitude and latitude)
- PGA and PGD
- Classification (i.e. stationary or rail mounted)

Fuel Facilities

- Geographical location of facility [longitude and latitude]
- PGA and PGD
- Classification

Warehouses

- Geographical location of warehouse [longitude and latitude]
- PGA and PGD
- Classification (i.e. building type)

Direct damage output for port systems includes probability estimates of (1) component functionality and (2) physical damage, expressed in terms of the component's damage ratio. Damage ratios are used as inputs to direct economic loss methods, as described in section 15.3 of Chapter 15.

7.5.4 Form of Damage Functions

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

- For waterfront structures, the fragility curves are defined in terms of PGD and PGA.

- For cranes/cargo handling equipment, the fragility curves are defined in terms of PGA and PGD.

- For fuel facilities, the fragility curves are defined in terms of PGA and PGD.

- For warehouses, the fragility curves are defined in terms of PGA and PGD.

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

7.5.5 Description of Port Components

A port system consists of four components: waterfront structures, cranes/cargo handling equipment, fuel facilities, and warehouses. This section provides a brief description of each.

Waterfront Structures

This component includes wharves (port embankments), seawalls (protective walls from erosion), and piers (break-water structures which form harbors) that exist in the port system. Waterfront structures typically are supported by wood, steel or concrete piles. Many also have batter piles to resist lateral loads from wave action and impact of vessels. Seawalls are caisson walls retaining earth fill material.

Cranes and Cargo Handling Equipment

These are large equipment items used to load and unload freight from vessels. These are can be stationary or mounted on rails.

Port Fuel Facilities

The fuel facility consists mainly of fuel storage tanks, buildings, pump equipment, piping, and, sometimes, backup power. These are the same as those for railway systems presented in Section 7.2. The functionality of fuel systems is determined with a fault tree analysis, which considers redundancies and sub-component behavior, as it can be seen in Figures 7.18 and 7.19 of Section 7.2. Note that five types of fuel facilities in total are defined.

Warehouses

Warehouses are large buildings usually constructed of structural steel. In some cases, warehouses may be several hundred feet from the shoreline, while in other instances; they may be located on the wharf itself.

7.5.6 Definition of Damage States

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

Slight/Minor Damage (ds_2)

- For waterfront structures, ds_2 is defined by minor ground settlement resulting in few piles (for piers/seawalls) getting broken and damaged. Cracks are formed on the surface of the wharf. Repair may be needed.

- For cranes/cargo handling equipment, ds_2 is defined by slight damage to structural members with no loss of function for the stationary equipment, while for the unanchored or rail mounted equipment, ds_1 is defined as minor derailment or misalignment without any major structural damage to the rail mount. Minor repair and adjustments may be required before the crane becomes operable.

- For fuel facilities, ds_2 is defined the same as for railway facilities.

- For warehouses, ds_2 is defined by slight damage to the warehouse building.

Moderate Damage (ds_3)

- For waterfront structures, ds_3 is defined as considerable ground settlement with several piles (for piers/seawalls) getting broken and damaged.

- For cranes/cargo handling equipment, ds_3 is defined as derailment due to differential displacement of parallel track. Rail repair and some repair to structural members is required.

- For fuel facilities, ds_3 is defined the same as for railway facilities.

- For warehouses, ds_3 is defined by moderate damage to the warehouse building.

Extensive Damage (ds_4)

- For waterfront structures, ds_4 is defined by failure of many piles, extensive sliding of piers, and significant ground settlement causing extensive cracking of pavements.

- For cranes/cargo handling equipment, ds_4 is defined by considerabe damage to equipment. Toppled or totally derailed cranes are likely to occcur. Replacement of structural members is required.

- For fuel facilities, ds_4 is defined same as for railway facilities.

- For warehouses, ds_4 is defined by extensive damage to warehouse building.

Complete Damage (ds_5)

- For waterfront structures, ds_5 is defined as failure of most piles due to significant ground settlement. Extensive damage is widespread at the port facility.

- For cranes/cargo handling equipment, ds_5 is the same as ds_4.
- For fuel facilities with buried tanks, ds_5 is the same as for railway facilities.
- For warehouses, ds_5 is defined by total damage to the warehouse building.

7.5.7 Component Restoration Curves

Restoration Curves are developed based on a best fit to ATC-13 damage data for social functions SF 28.a and SF 29.b, consistent with damage states defined in the previous section. Normal distribution functions are developed using the ATC-13 data for the mean time for 30%, 60% and 100% restoration of different sub-components in different damage states. Means and dispersions of these restoration functions are given in Table 7.14.a. The discretized restoration functions are given in Table 7.14.b, where the percentage restoration is shown at some specified time intervals. These restoration functions are shown in Figures 7.23 and 7.24. Figure 7.23 represents restoration curves for waterfront structures, while Figure 7.24 shows restorations curve for cranes and cargo handling equipment.

Table 7.14.a Restoration Functions for Port Sub-Components

Restoration Functions (All Normal Distributions)			
Classification	**Damage State**	**Mean (Days)**	**σ**
Buildings, Waterfront Structures	slight/minor	0.6	0.2
	moderate	3.5	3.5
	extensive	22	22
	complete	85	73
Cranes/Cargo Handling Equipment	slight/minor	0.4	0.35
	moderate	6	6
	extensive	30	30
	complete	75	55

Table 7.14.b Discretized Restoration Functions for Port Sub-Components

Discretized Restoration Functions						
Classification	**Damage State**	**1 day**	**3 days**	**7 days**	**30 days**	**90 days**
Buildings, Waterfront Structures	slight/minor	96	100	100	100	100
	moderate	24	43	84	100	100
	extensive	17	19	25	63	100
	complete	12	13	14	22	53
Cranes/Cargo Handling Equipment	slight/minor	96	100	100	100	100
	moderate	20	31	57	100	100
	extensive	17	18	22	50	100
	complete	9	10	11	21	62

7.5.8 Development of Damage Functions

Damage functions for port system facilities are defined in terms of PGA and PGD. Note that, unless it is specified otherwise, ground failure (PGD) related damage functions for these facilities are assumed to be similar to those described for railroad system facilities in section 7.2.8.

An example of how to combine PGD and PGA algorithms is presented in section 7.2.8.

Damage functions for Waterfront Structures

Damage functions for waterfront structures were established based on damagability of subcomponents, namely, piers, seawalls, and wharf. Fault tree logic and the lognormal best fitting technique were used in developing these fragility curves. The fault tree is implicitly described in the description of the damage state. The obtained damage functions are shown in Figure 7.25. Their medians and dispersions are presented in Table 7.15a. Subcomponent damage functions are given in Table 7.D.1 of Appendix 7D.

Table 7.15.a Damage Algorithms for Waterfront Structures

Permanent Ground Deformation			
Components	**Damage State**	**Median (in)**	**β**
Waterfront Structures (PWS1)	slight/minor	5	0.50
	moderate	12	0.50
	extensive	17	0.50
	complete	43	0.50

Damage Functions for Cranes and Cargo Handling Equipment

For cranes, a distinction is made between stationary and rail-mounted cranes. The medians and dispersions of damage functions are presented in Tables 7.15.b, while the fragility curves are shown in Figures 7.26 through 7.29.

Table 7.15.b Damage Algorithms for Cranes/Cargo Handling Equipment

Peak Ground Acceleration			
Classification	**Damage State**	**Median (g)**	**β**
Anchored/ Stationary (PEQ1)	slight/minor	0.3	0.6
	moderate	0.5	0.6
	extensive/complete	1.0	0.7
Unanchored/Rail mounted (PEQ2)	slight/minor	0.15	0.6
	moderate	0.35	0.6
	extensive/complete	0.8	0.7

Permanent Ground Deformation			
Classification	**Damage State**	**Median (in)**	**β**
Anchored/ Stationary (PEQ1)	slight/minor	3	0.6
	moderate	6	0.7
	extensive/complete	12.0	0.7
Unanchored/Rail mounted (PEQ2)	slight/minor	2	0.6
	moderate	4.0	0.6
	extensive/complete	10	0.7

Damage Functions for Port System Fuel Facilities

Damage funcitons for fuel facilities are similar to those developed for railway fuel facilities in Section 7.2.8.

PGA Related Damage Functions for Warehouses

Since no default inventory is provided for these facilities, the user will be expected to provide the appropriate mapping bewteen these facilities and the building types which are assumed to be the same as for railway maintenance facilities whose damage functions are listed in Table 7.7 of section 7.2.8.

7.5.9 Guidance for Loss Estimation using Advanced Data and Models Analysis

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

7.5.10 References

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

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

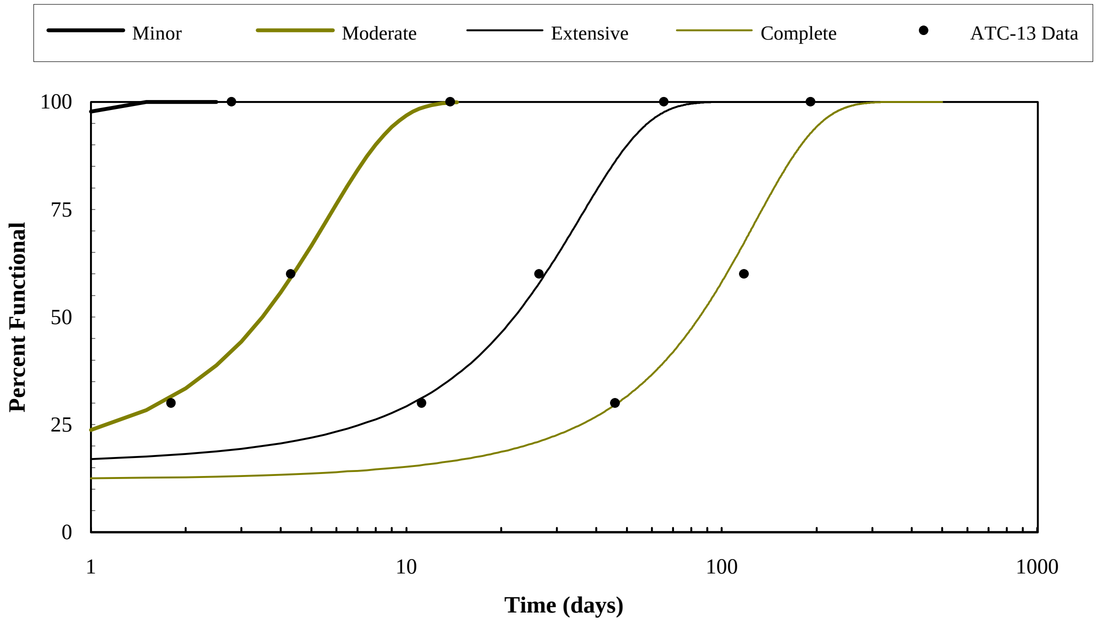


Figure 7.23 Restoration Curves for Port Waterfront Structures.

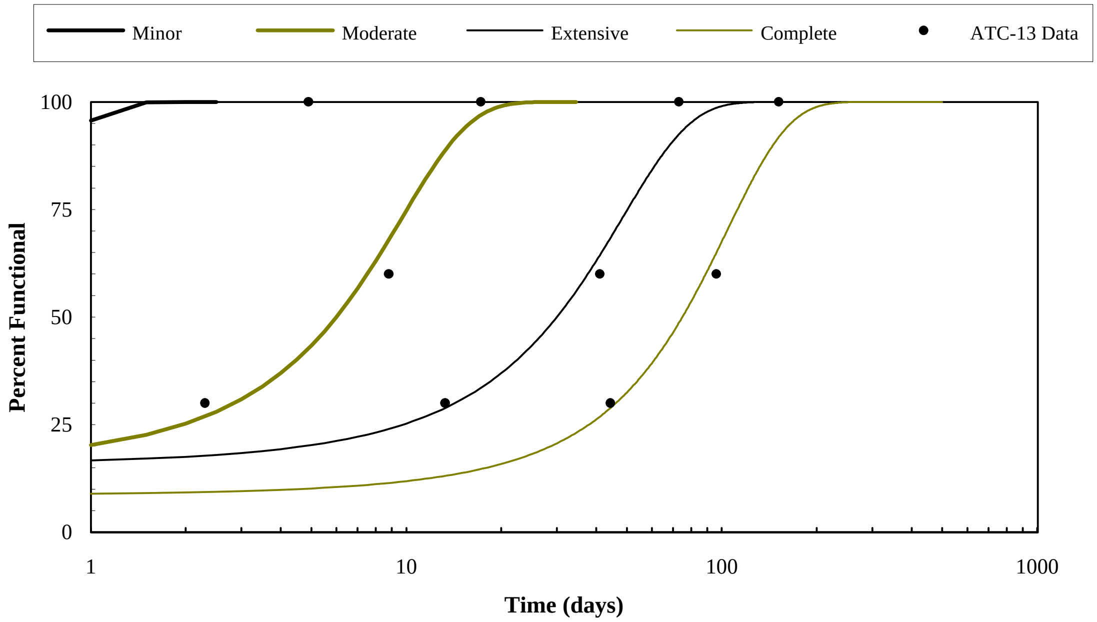


Figure 7.24 Restoration Curves for Cranes/Cargo Handling Equipment.

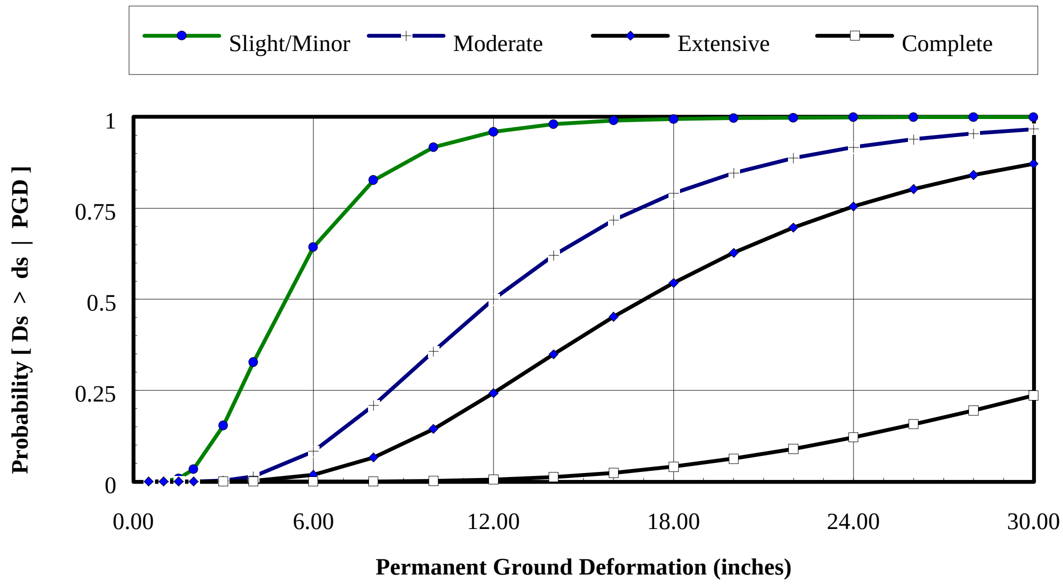


Figure 7.25 Fragility Curves for Waterfront Structures.

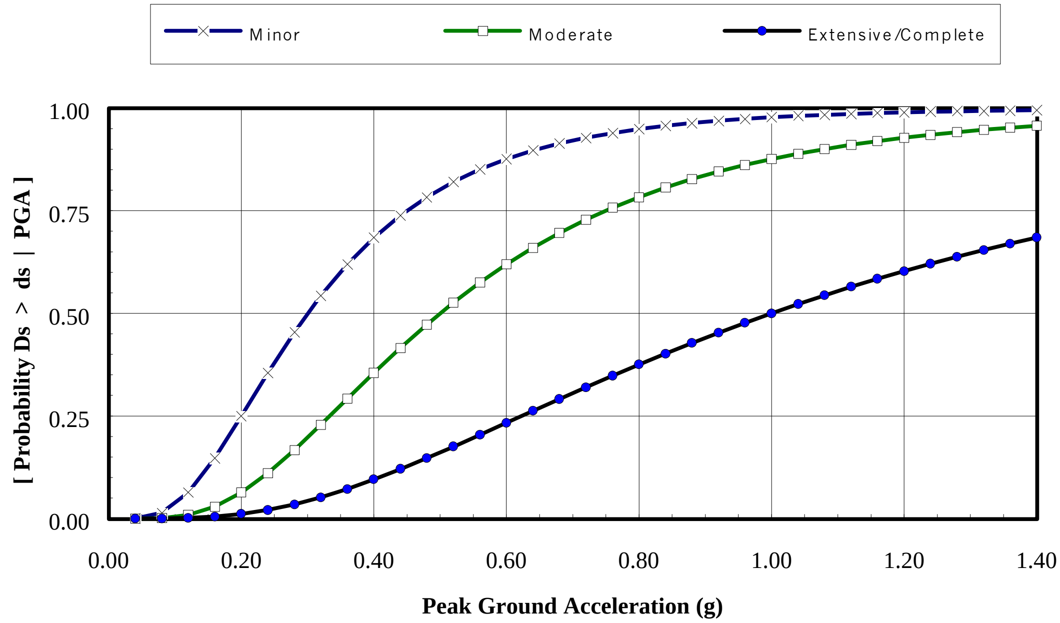


Figure 7.26 Fragility Curves for Stationary Cranes/Cargo Handling Equipment Subject to Peak Ground Acceleration.

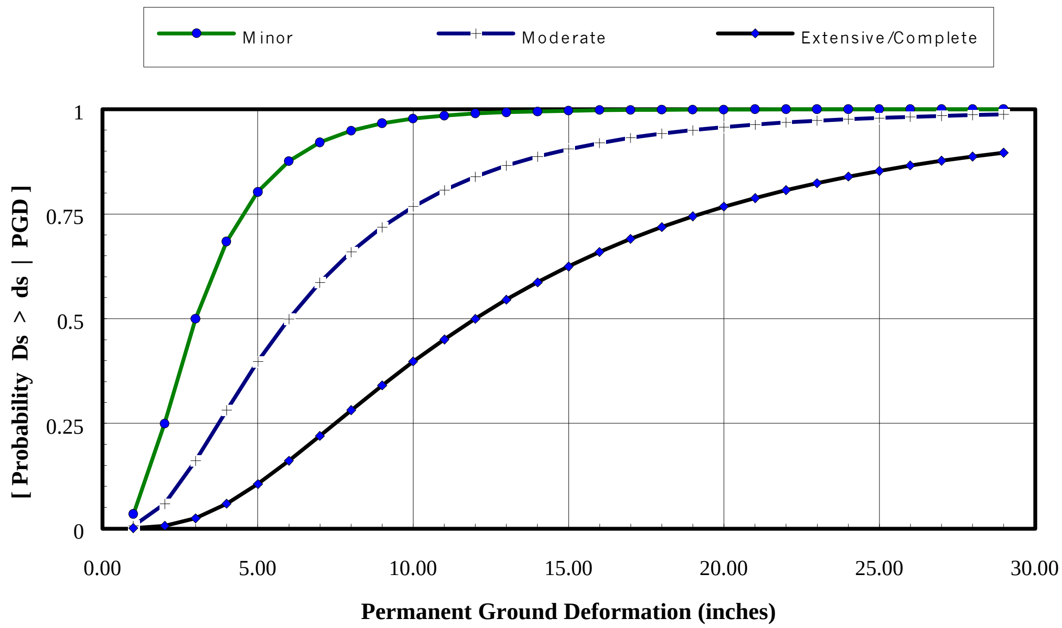


Figure 7.27 Fragility Curves for Stationary Cranes/Cargo Handling Equipment Subject to Permanent Ground Deformation.

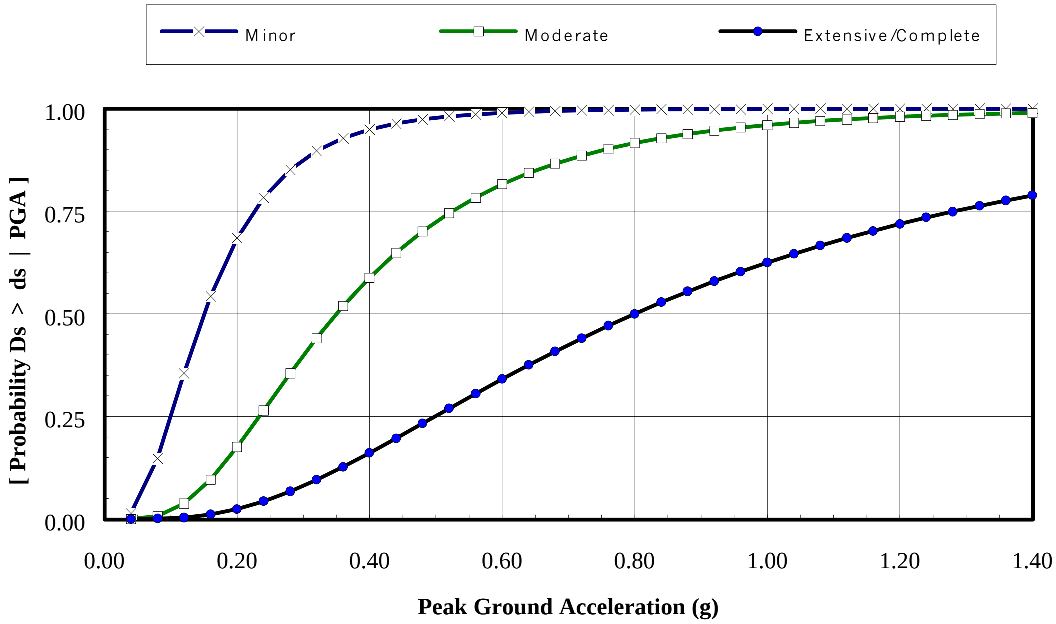


Figure 7.28 Fragility Curves for Rail Mounted Cranes/Cargo Handling Equipment Subject to Peak Ground Acceleration.

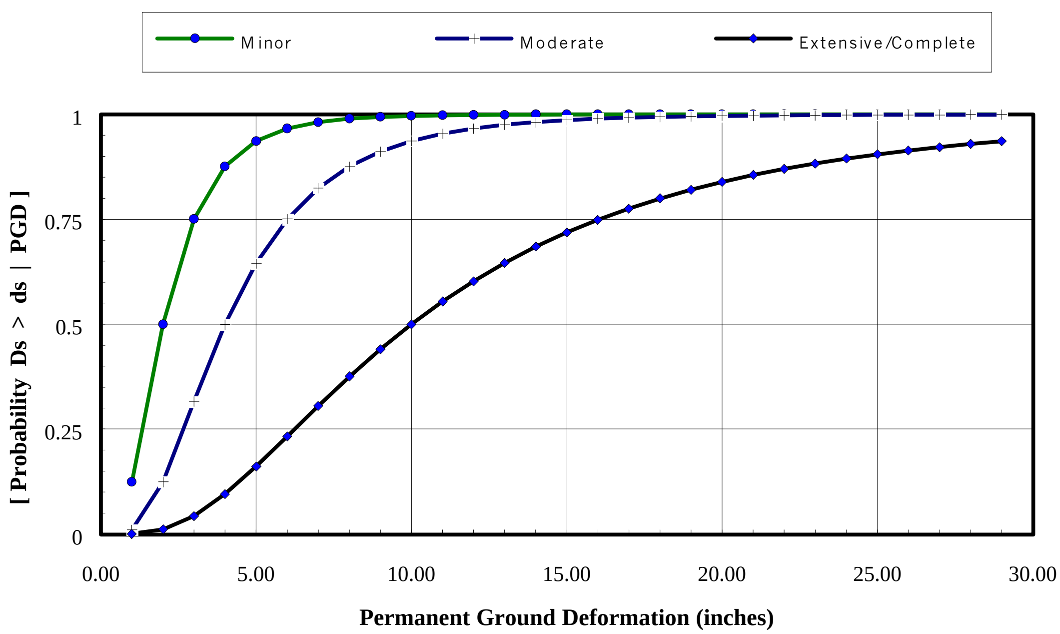


Figure 7.29 Fragility Curves for Rail Mounted Cranes/Cargo Handling Equipment Subject to Permanent Ground Deformation.

7.6 Ferry Transportation System

7.6.1 Introduction

This section presents a loss estimation methodology for a ferry transportation system. Ferry systems consist of waterfront structures (e.g., wharf, piers and seawalls); fuel, maintenance, and dispatch facilities; and passenger terminals.

The waterfront structures are located at the points of embarkation or disembarkation, and they are similar to, although not as extensive as, those of the port transportation system. In some cases the ferry system may be located within the boundary of the port transportation system. The points of embarkation or disembarkation are located some distance apart from one another, usually on opposite shorelines.

Fuel and maintenance facilities are usually located at one of these two points. The size of the fuel facility is smaller than that of the port facility. In many cases, the dispatch facility is located in the maintenance facility or one of the passenger terminals.

7.6.2 Scope

The scope of this section includes development of methods for estimation of earthquake damage to a ferry transportation system given knowledge of components (i.e., waterfront structures; fuel, maintenance, and dispatch facilities; and passenger terminals), classification (i.e. for fuel facilities, anchored or unanchored components, with or without back-up power), and the ground motion (i.e. peak ground acceleration and/or permanent ground deformation).

Damage states describing the level of damage to each of the ferry system components are defined (i.e. slight/minor, moderate, extensive or complete). Damage states are related to damage ratio (defined as ratio of repair to replacement cost) for evaluation of direct economic loss. Component restoration curves are provided for each damage state to evaluate loss of function. Restoration curves describe the fraction or percentage of the component that is expected to be open or operational as a function of time following the earthquake. For ferries the restoration is dependent upon the extent of damage to the waterfront structures; fuel, maintenance, and dispatch facilities; and passenger terminals.

Fragility curves are developed for each class of the ferry system components. These curves describe the probability of reaching or exceeding each damage state given the level of ground motion. Based on these fragility curves, a method for assessing functionality of each of the five ferry system components is presented.

Interdependence of components on overall system functionality is not addressed by the methodology. Such considerations require a system (network) analysis that would be performed separately by a transportation system expert as an advanced study.

7.6.3 Input Requirements and Output Information

Required input to estimate damage to ferry systems includes the following items:

Ferry Waterfront Structures
- Geographic locations of harbor
- PGA & PGD

Ferry Fuel Facilities
- Geographical location of facility
- PGA and PGD
- Classification

Ferry Maintenance Facilities
- Geographical location of facility
- PGA and PGD
- Classification (i.e. building type)

Ferry Dispatch Facilities
- Geographical location of facility
- PGA and PGD
- Classification

Ferry Terminal Buildings
- Geographical location of building
- PGA and PGD
- Classification (i.e. building type)

Direct damage output for ferry systems includes probability estimates of (1) component functionality and (2) physical damage, expressed in terms of the component's damage ratio. Damage ratios are used as inputs to direct economic loss methods, as described in section 15.3 of Chapter 15.

7.6.4 Form of Damage Functions

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

- For waterfront structures, the fragility curves are defined in terms of PGA & PGD.

- For fuel facilities, maintenance and dispatch facilities; and terminal building, the fragility curves are defined in terms of PGA and PGD.

Definitions of various damage states and the methodology used in deriving fragility curves for ferry system components are presented in the following subsections.

7.6.5 Description of Ferry System Components

A ferry system consists of the five components mentioned above: waterfront structures, fuel facilities, maintenance facilities, dispatch facilities, and passenger terminals. This section provides a brief description of each.

Waterfront Structures
These are the same as those for port systems described in Section 7.5.5.

Fuel Facilities
These facilities are similar to those for port system mentioned in Section 7.5.5.

Maintenance Facilities
These are often steel braced frame structures, but other building types are possible.

Dispatch Facilities
These are similar to those defined for railway system in Section 7.2.5.

Passenger Terminals
These are often moment resisting steel frames, but other building types are possible.

7.6.6 Definitions of Damage States

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

Slight/Minor Damage (ds_2)

- For waterfront structures, ds_2 is the same as that for waterfront structures in the port module.

- For fuel facilities, ds_2 is the same as that for fuel facilities in the port module.

- For maintenance facilities, ds_2 is defined by slight damage to building.

- For dispatch facilities, ds_2 is the same as that for dispatch facilities in the railway module.
- For passenger terminals, ds_2 is defined by slight damage to building.

Moderate Damage (ds_3)

- For waterfront structures, ds_3 is the same as that for waterfront structures in the port module.
- For fuel facilities, ds_3 is the same as that for fuel facilities in the port module.
- For maintenance facilities, ds_3 is defined by moderate damage to building.
- For dispatch facilities, ds_3 is the same as that for dispatch facilities in the railway module.
- For passenger terminals, ds_3 is defined by moderate damage to building.

Extensive Damage (ds_4)

- For waterfront structures, ds_4 is the same as that for waterfront structures in the port module.
- For fuel facilities, ds_4 is the same as that for fuel facilities in the port module.
- For maintenance facilities, ds_4 is defined by extensive damage to building.
- For dispatch facilities, ds_4 is the same as that for dispatch facilities in the railway module.
- For passenger terminals, ds_4 is defined by extensive damage to building.

Complete Damage (ds_5)

- For waterfront structures, ds_5 is the same as that for waterfront structures in the port module.
- For fuel facilities, ds_5 is the same as that for fuel facilities in the port module.
- For maintenance facilities, ds_5 is defined by complete damage to building.
- For dispatch facilities, ds_5 is the same as that for dispatch facilities in the railway module.

- For passenger terminals, ds_5 is defined as complete damage to building.

7.6.7 Component Restoration Curves

Ferry systems are made of components that are similar to either those in port systems (i.e. waterfront structures, fuel facilities), or those in railway systems (i.e. dispatch facilities, maintenance facilities, passenger terminals). Therefore, restoration curves for ferry system components can be found in either Section 7.5 or Section 7.2.

7.6.8 Development of Damage Functions

Similar to restoration curves, damage functions for ferry system components can be found in either Section 7.5 or Section 7.2.

7.6.9 Guidance for Loss Estimation Using Advanced Data and Models Analysis

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

7.6.10 References

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

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

7.7 Airport Transportation System

7.7.1 Introduction

This section presents a loss estimation methodology for an airport transportation system. Airport transportation system consists of runways, control tower, fuel facilities, terminal buildings, maintenance facilities, hangar facilities, and parking structures. For airports, control towers are often constructed of reinforced concrete, while terminal buildings and maintenance facilities are often constructed of structural steel or reinforced concrete. Fuel facilities are similar to those for railway transportation systems.

7.7.2 Scope

The scope of this section includes development of methods for estimation of earthquake damage to an airport transportation system given knowledge of components (i.e. runways, control tower, fuel, and maintenance facilities, terminal buildings, and parking structures), classification, and ground motion (i.e. peak ground acceleration and/or permanent ground deformation).

Damage states describing the level of damage to each of the airport system components are defined (i.e. slight, moderate, extensive or complete). Damage states are related to damage ratio (defined as ratio of repair to replacement cost) for evaluation of direct economic loss. Component restoration curves are provided for each damage state to evaluate loss of function. Restoration curves describe the fraction or percentage of the component that is expected to be open or operational as a function of time following the earthquake. For airports, the restoration is dependent upon the extent of damage to the airport terminals, buildings, storage tanks (for fuel facilities), control tower, and runways.

Fragility curves are developed for each component class of the airport system. These curves describe the probability of reaching or exceeding each damage state given the level of ground motion. Based on these fragility curves, a method for assessing functionality of each of the six airport system components is presented.

7.7.3 Input Requirements and Output Information

Required input to estimate damage to airport systems includes the following items:

Runways

- Geographic location of airport [longitude and latitude]
- PGD

Control Tower

- Geographic location of airport [longitude and latitude]

- PGA and PGD
- Classification (i.e. building type)

<u>Fuel Facilities</u>

- Geographical location of facility [longitude and latitude]
- PGA and PGD
- Classification

<u>Terminal Buildings</u>

- Geographical location of airport [longitude and latitude]
- PGA and PGD
- Classification (i.e. building type)

<u>Maintenance and Hangar Facilities</u>

- Geographical location of facility [longitude and latitude]
- PGA and PGD
- Classification (i.e. building type)

<u>Parking Structures</u>

- Geographical location of structure [longitude and latitude]
- PGA and PGD
- Classification (i.e. building type)

Direct damage output for airport systems includes probability estimates of (1) component functionality and (2) physical damage, expressed in terms of the component's damage ratio. Damage ratios are used as inputs to direct economic loss methods, as described in section 15.3 of Chapter 15.

7.7.4 Form of Damage Functions

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

- For runways, the fragility curves are defined in terms of PGD.

- For control towers, the fragility curves are defined in terms of PGA and PGD.
- For all other facilities, the fragility curves are defined in terms of PGA and PGD.

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

7.7.5 Description of Airport Components

An airport system consists of the six components mentioned above: runways, control tower, fuel facilities, maintenance facilities, and parking structures. This section provides a brief description of each.

Runways
This component consists of well-paved "flat and wide surfaces".

Control Tower
Control tower consists of a building and the necessary equipment of air control and monitoring.

Fuel Facilities
These have been previously defined in Section 7.2.5 of railway systems.

Terminal Buildings
These are similar to urban stations of railway systems from the classification standpoint (as well as services provided to passengers).

Maintenance Facilities, Hangar Facilities, and Parking Structures
Classification of maintenance facilities is the same as for those in railway systems. Hangar facilities and parking structures are mainly composed of buildings.

7.7.6 Definitions of Damage States

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

Slight/Minor Damage (ds_2)

- For runways, ds_2 is defined as minor ground settlement or heaving of runway surface.
- For control tower, ds_2 is defined as slight damage to the building as given in section 5.3.

- For fuel facilities, ds_2 is the same as that for fuel facilities in the railway module.
- For terminal buildings, ds_2 is defined as slight damage to the building as given in section 5.3.
- For maintenance and hangar facilities, ds_2 is defined as slight damage to the building as given in section 5.3.
- For parking structures, ds_2 is defined as slight damage to the building as given in section 5.3.

Moderate Damage (ds_3)

- For runways, ds_3 is defined same as ds_2.
- For control tower, ds_3 is defined as moderate damage to the building as given in section 5.3.
- For fuel facilities, ds_3 is the same as that for fuel facilities in the railway module.
- For terminal buildings, ds_3 is defined as moderate damage to the building as given in section 5.3.
- For maintenance and hangar facilities, ds_3 is defined as moderate damage to the building as given in section 5.3.
- For parking structures, ds_3 is defined as moderate damage to the building as given in section 5.3.

Extensive Damage (ds_4)

- For runways, ds_4 is defined as considerable ground settlement or considerable heaving of runway surface.
- For control tower, ds_4 is defined as extensive damage to the building as given in section 5.3.
- For fuel facilities, ds_4 is the same as that for fuel facilities in the railway module.
- For terminal buildings, ds_4 is defined as extensive damage to the building as given in section 5.3.
- For maintenance and hangar facilities, ds_4 is defined as extensive damage to the building as given in section 5.3.

- For parking structures, ds_4 is defined as extensive damage to the building as given in section 5.3.

Complete Damage **(ds_5)**

- For runways, ds_5 is defined as extensive ground settlement or excessive heaving of runway surface.
- For control tower, ds_5 is defined as complete damage to the building as given in section 5.3.
- For fuel facilities, ds_5 is the same as that for fuel facilities in the railway module.
- For terminal buildings, ds_5 is defined as complete damage to the building as given in section 5.3.
- For maintenance and hangar facilities, ds_5 is defined as complete damage to the building as given in section 5.3.
- For parking structures, ds_5 is defined as complete damage to the building as given in section 5.3.

7.7.7 Component Restoration Curves

Restoration Curves are developed based on a best fit to ATC-13 data for social functions SF 27.a and SF 27.b, consistent with damage states defined in the previous section. Normal distribution functions are developed using this ATC-13 data for the mean time for 30%, 60% and 100% restoration. Means and dispersions of these restoration functions are given in Table 7.16.a and shown in Figures 7.30 and 7.31. The discretized restoration functions are presented in Table 7.16.b, where the percentage restoration is shown at selected time intervals.

Table 7.16.a Restoration Functions for Airport Components

Restoration Functions (All Normal Distributions)			
Classification	**Damage State**	**Mean (Days)**	**σ**
Control Towers, Parking Structures, Hangar Facilities, Terminal Building	slight	0	0
	moderate	1.5	1.5
	extensive	50	50
	complete	150	120
Runways	slight/moderate	2.5	2.5
	extensive	35	35
	complete	85	65

Table 7.16.b Discretized Restoration Functions for Aiport Sub-Components

Discretized Restoration Functions						
Classification	**Damage State**	**1 day**	**3 days**	**7 days**	**30 days**	**90 days**
Control Towers, Parking Structures, Hangar Facilities, Terminal Building	slight	100	100	100	100	100
	moderate	37	84	100	100	100
	extensive	16	17	20	34	79
	complete	11	11	12	16	31
Runways	slight/moderate	27	57	100	100	100
	extensive	17	18	21	44	95
	complete	10	11	12	20	53

7.7.8 Development of Damage Functions

Damage functions for airport system facilities are defined in terms of PGA and PGD except for runways (PGD only). Note that, unless it is specified otherwise, ground failure (PGD) related damage functions for these facilities are assumed to be similar to those described for railroad system facilities in section 7.2.8.

An example of how to combine PGD and PGA algorithms is presented in section 7.2.8.

Damage Functions for Runways

The earthquake hazard for airport runways is ground failure. Little damage is attributed to ground shaking; therefore, the damage function includes only ground failure as the hazard. All runways are assumed to be paved. The median values and dispersion for the damage states for runways are given in Table 7.17. These damage functions are also shown in Figure 7.32.

Table 7.17 Damage Algorithms for Runways

Permanent Ground Deformation			
Classification	**Damage State**	**Median (in)**	**β**
Runways	slight/moderate	1	0.6
	extensive	4	0.6
	complete	12	0.6

Damage Functions for Rest of Airport System Components

In section 7.7.5, these components were defined by "one to one" correspondence with those for railway systems. Therefore, damage functions for the remaining airport components (i.e. fuel facilities, maintenance facilities, and other buildings) can be found in Section 7.2.8.

7.7.9 Guidance for Loss Estimation Using Advanced Data and Models Analysis

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

7.7.10 References

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

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

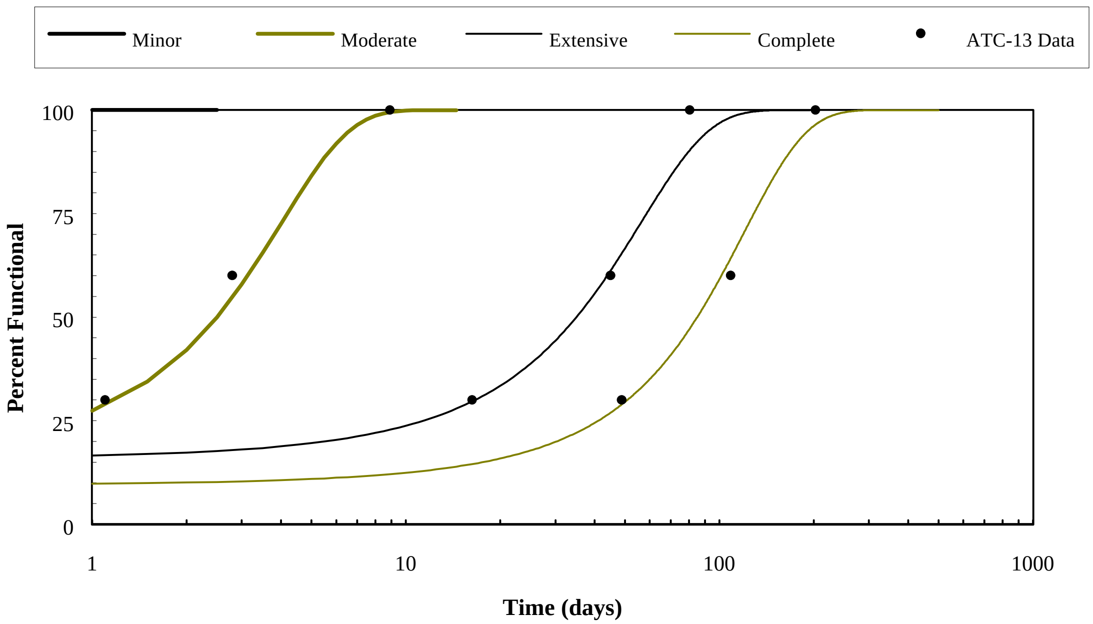


Figure 7.30 Restoration Curve for Airport Runways.

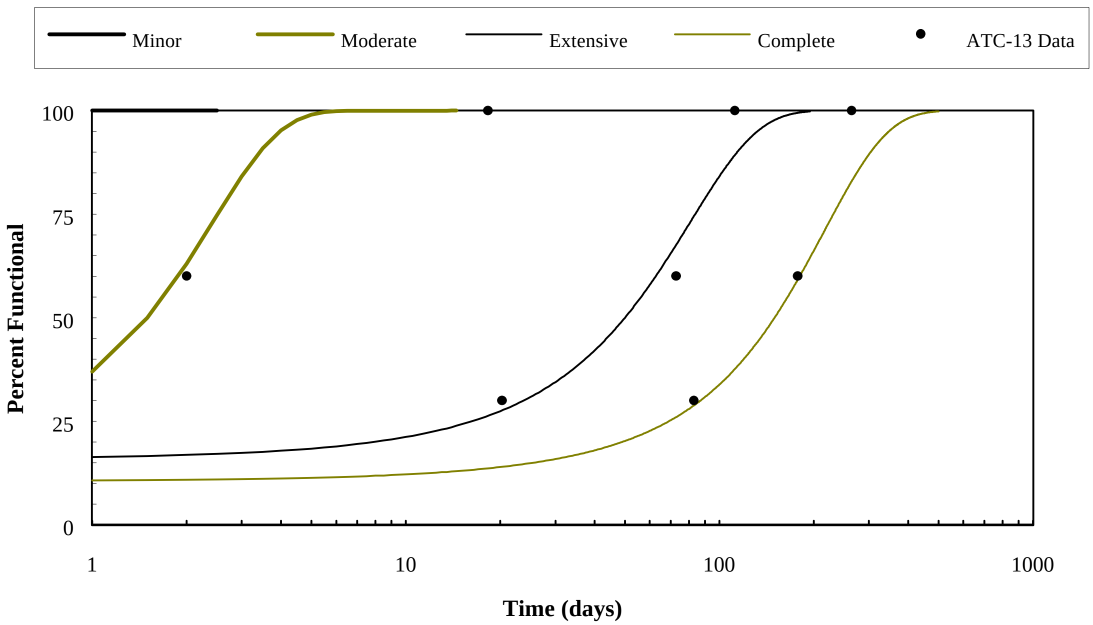


Figure 7.31 Restoration Curves for Airport Buildings, Facilities, and Control Tower.

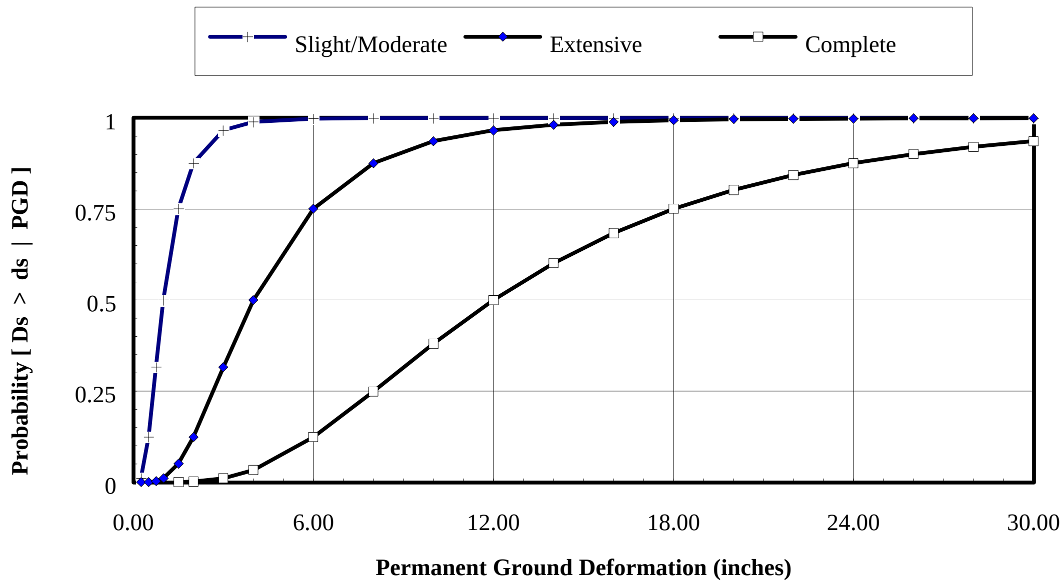


Figure 7.32 Fragility Curves for Runways Subject to Permanent Ground Deformation at Various Damage States.

APPENDIX 7A

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

Table A.7.1 Subcomponent Damage Algorithms: Rock Tunnels (after G&E, 1994)

Peak Ground Acceleration			
Subcomponents	Damage State	Median (g)	β
Liner	slight moderate	0.6 0.8	0.4 0.6

Permanent Ground Deformation			
Subcomponents	Damage State	Median (in)	β
Liner	slight extensive complete	6 12 60	0.7 0.5 0.5
Portal	slight extensive complete	6 12 60	0.7 0.5 0.5

Table A.7.2 Subcomponent Damage Algorithms: Cut & Cover Tunnels (after G&E, 1994)

Peak Ground Acceleration			
Subcomponents	Damage State	Median (g)	β
Liner	slight moderate	0.5 0.7	0.4 0.6

Permanent Ground Deformation			
Subcomponents	Damage State	Median (in)	β
Liner	slight extensive complete	6 12 60	0.7 0.5 0.5
Portal	slight extensive complete	6 12 60	0.7 0.5 0.5

APPENDIX 7B

Table B.7.1 Subcomponent Damage Algorithms: Seismically Designed Railway Bridges (after G&E, 1994)

Peak Ground Acceleration			
Subcomponents	**Damage State**	**Median (g)**	**β**
Column	slight	0.45	0.55
	extensive	1.0	0.7
	complete	1.4	0.7
Abutment	slight	0.45	0.55
	moderate	1.0	0.7
Connection	moderate	0.86	0.70
	extensive	1.4	0.70
Deck	slight	0.67	0.55

Permanent Ground Deformation			
Subcomponents	**Damage State**	**Median (in)**	**β**
Column	extensive	14	0.7
	complete	28	0.7
Abutment	moderate	15	0.7
	extensive	30	0.7
Connection	complete	30	0.7
Approach	slight	2	0.5
	moderate	12	0.7
	extensive	24	0.7

Table B.7.2 Subcomponent Damage Algorithms: Conventionally Designed Railway Bridges (after G&E, 1994)

Peak Ground Acceleration			
Subcomponents	**Damage State**	**Median (g)**	**β**
Column	slight extensive complete	0.3 0.8 1.0	0.55 0.7 0.7
Abutment	slight moderate	0.3 0.8	0.55 0.7
Connection	moderate extensive	0.7 1.0	0.70 0.70
Deck	slight	0.5	0.55

Permanent Ground Deformation			
Subcomponents	**Damage State**	**Median (in)**	**β**
Column	extensive complete	10 21	0.7 0.7
Abutment	moderate extensive	10 21	0.7 0.7
Connection	complete	21	0.7
Approach	slight moderate extensive	2 12 24	0.5 0.7 0.7

Table B.7.3 Subcomponent Damage Algorithms:
Fuel Facility with Anchored Components (after G&E, 1994)

Peak Ground Acceleration			
Subcomponents	**Damage State**	**Median (g)**	**β**
Electric Power (Backup)	slight moderate	0.80 1.00	0.60 0.80
Electric Power (Off-Site)	slight moderate	0.15 0.25	0.6 0.5
Tank	slight moderate extensive complete	0.30 0.70 1.25 1.60	0.60 0.60 0.65 0.60
Pump Building	slight moderate extensive complete	0.15 0.40 0.80 1.50	0.80 0.80 0.80 0.80
Horizontal Pump	extensive	1.60	0.60
Equipment	moderate	1.00	0.60

Table B.7.4 Subcomponent Damage Algorithms:
Fuel Facility with Unanchored Components (after G&E, 1994)

Peak Ground Acceleration			
Subcomponents	**Damage State**	**Median (g)**	**β**
Electric Power (Backup)	slight moderate	0.20 0.40	0.60 0.80
Electric Power (Off-Site)	slight moderate	0.15 0.25	0.6 0.5
Tank	slight moderate extensive complete	0.15 0.35 0.68 0.95	0.70 0.75 0.75 0.70
Pump Building	slight moderate extensive complete	0.15 0.40 0.80 1.50	0.80 0.80 0.80 0.80
Horizontal Pump	extensive	1.60	0.60
Equipment	moderate	0.60	0.60

Table B.7.5 Subcomponent Damage Algorithms: Dispatch Facility with Anchored Components (after G&E, 1994)

Peak Ground Acceleration			
Subcomponents	**Damage State**	**Median (g)**	**β**
Electric Power (Backup)	slight moderate	0.80 1.00	0.60 0.80
Electric Power (Off-Site)	slight moderate	0.15 0.25	0.6 0.5
Building	slight moderate extensive complete	0.15 0.40 0.80 1.50	0.80 0.80 0.80 0.80
Equipment	moderate	1.00	0.60

Table B.7.6 Subcomponent Damage Algorithms: Dispatch Facility with Unanchored Components (after G&E, 1994)

Peak Ground Acceleration			
Subcomponents	**Damage State**	**Median (g)**	**β**
Electric Power (Backup)	slight moderate	0.20 0.40	0.60 0.80
Electric Power (Off-Site)	slight moderate	0.15 0.25	0.6 0.5
Building	slight moderate extensive complete	0.15 0.40 0.80 1.50	0.80 0.80 0.80 0.80
Equipment	moderate	0.60	0.60

APPENDIX 7C

Table C.7.1 Subcomponent Damage Algorithms for DC Power Substation with Anchored Components

Peak Ground Acceleration			
Subcomponents	Damage State	Median (g)	β
Building	slight moderate extensive complete	0.15 0.40 0.80 1.50	0.80 0.80 0.80 0.80
Equipment	moderate	1.00	0.60
Off-Site Power	slight moderate	0.15 0.25	0.6 0.5

Table C.7.2 Subcomponent Damage Algorithms for DC Power Substation with Unanchored Components

Peak Ground Acceleration			
Subcomponents	Damage State	Median (g)	β
Building	slight moderate extensive complete	0.15 0.40 0.80 1.50	0.80 0.80 0.80 0.80
Equipment	moderate	0.60	0.60
Off-Site Power	slight moderate	0.15 0.25	0.6 0.5

APPENDIX 7D

Table 7.D.1 Subcomponent Damage Algorithms for Waterfront Structures

Permanent Ground Deformation			
Subcomponents	**Damage State**	**Median (in)**	**β**
Wharf	slight	8	0.6
Piers	slight moderate extensive complete	8 16 24 60	0.6 0.6 0.6 0.6
Seawalls	slight moderate extensive complete	8 16 24 60	0.6 0.6 0.6 0.6

Chapter 8
Direct Damage to Lifelines - Utility Systems

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

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

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

8.1 Potable Water Systems

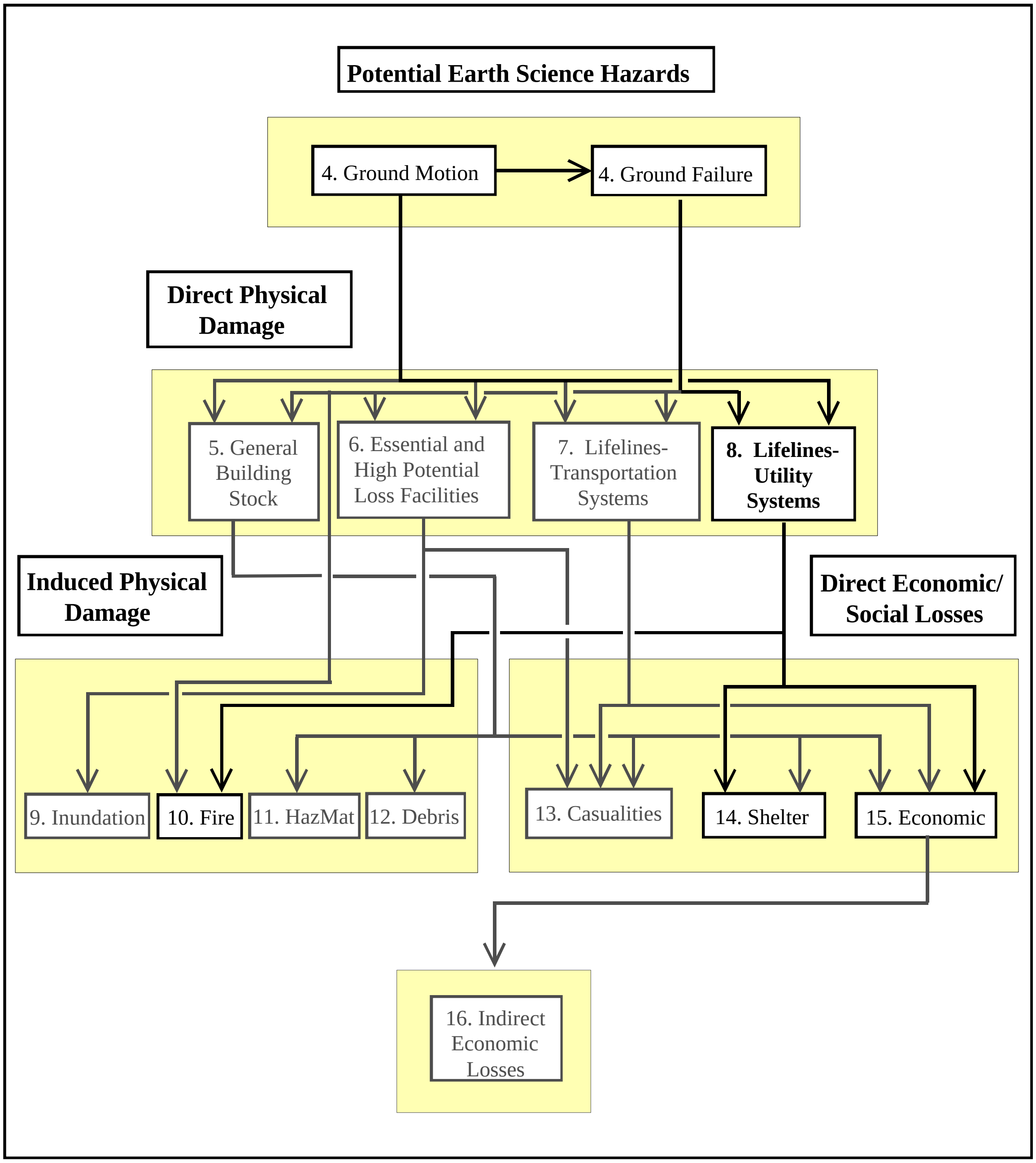
8.1.1 Introduction

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

8.1.2 Scope

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

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



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

8.1.3 Input Requirements and Output Information

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

Level One:

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

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

Level Two:

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

Transmission Aqueducts and Distribution Pipelines

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

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

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

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

Level Two Enhanced:

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

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

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

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

8.1.4 Form of Damage Functions

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

8.1.5 Description of Potable Water System Components

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

Terminal Reservoirs

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

Transmission Aqueducts

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

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

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

Supply Facilities- Water Treatment Plants (WTP)

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

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

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

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

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

Pumping Plants (PP)

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

Wells (WE)

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

Water Storage Tanks (ST)

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

Distribution Facilities and Distribution Pipes

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

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

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

8.1.6 Definition of Damage States

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

8.1.6.1 Damage State Defintions for Components Other than Pipelines

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

Slight/Minor Damage (ds_2)

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

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

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

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

Moderate Damage (ds_3)

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

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

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

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

<u>Extensive Damage</u> (ds_4)

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

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

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

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

<u>Complete Damage</u> (ds_5)

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

- **<u>For pumping plants</u>**, ds_5 is defined by the building collapsing.

- **<u>For wells</u>**, ds_5 is defined by the building collapsing.

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

8.1.6.2 Defintion of Damage States for Pipelines

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

8.1.7 Component Restoration Curves

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

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

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

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

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

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

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

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

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

Table 8.1.c: Restoration Functions for Potable Water Pipelines

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

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

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

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

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

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

8.1.8 Development of Damage Functions

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

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

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

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

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

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

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

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

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

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

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

Table 8.3: Damage Algorithms for Small Water Treatment Plants

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

Table 8.4: Damage Algorithms for Medium Water Treatment Plants

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

Table 8.5: Damage Algorithms for Large Water Treatment Plants

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

Damage Functions for Pumping Plants (due to Ground Shaking)

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

Table 8.6: Damage Algorithms for Small Pumping Plants

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

Table 8.7: Damage Algorithms for Medium/Large Pumping Plants

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

Damage Functions for Wells (due to Ground Shaking)

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

Table 8.8: Damage Algorithms for Wells

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

Damage Functions for Water Storage tanks

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

Table 8.9: Damage Algorithms for Water Storage Tanks

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

Damage Functions for Buried Pipelines

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

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

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

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

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

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

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

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

Table 8.10: Damage Algorithms for Water Pipelines

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

8.1.9 System Performance

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

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

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

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

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

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

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

Example

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

Table 8.11: Example of System Performance Evaluation

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

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

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

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

Hence, the serviceability index right after the earthquake is:

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

8.1.10 Guidance for Loss Estimation Using Advanced Data and Models Analysis

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

8.1.11 References

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

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

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

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(10) O'Rourke M.J and Ayala G., "Pipeline Damage due to Wave Propagation" Journal of Geotechnical Engineering, ASCE Vol 119, No.9, Sept. 1993.

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

(13) Khater M and Waisman F., "Potable Water System Analysis Model (POWSAM)", September 1999. NIBS technical report.

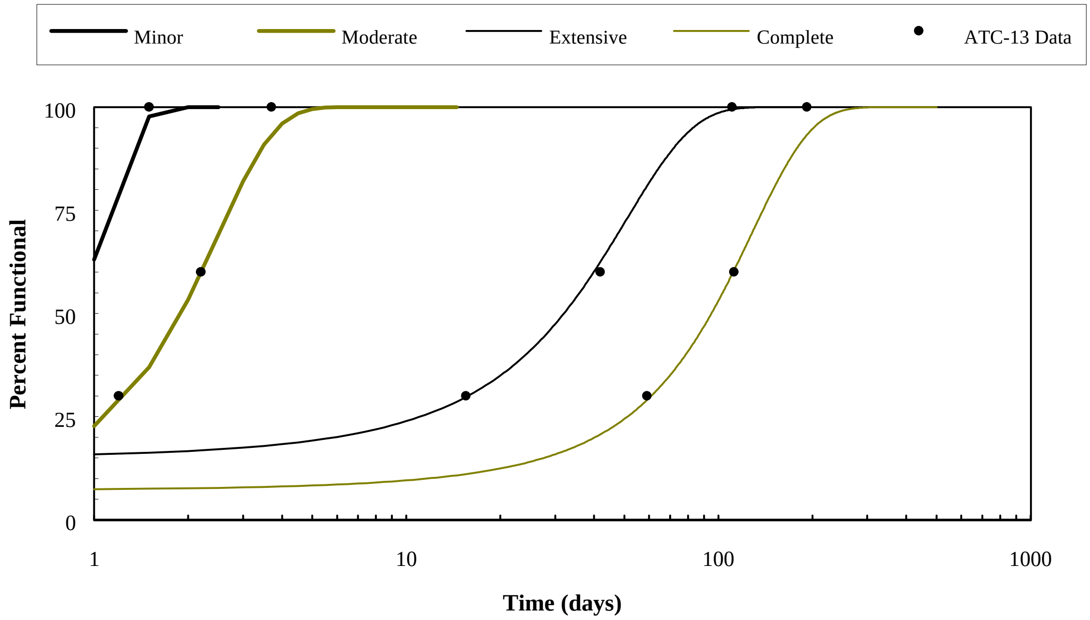


Figure 8.1: Restoration Curves for Water Treatment Plants (after ATC-13, 1985).

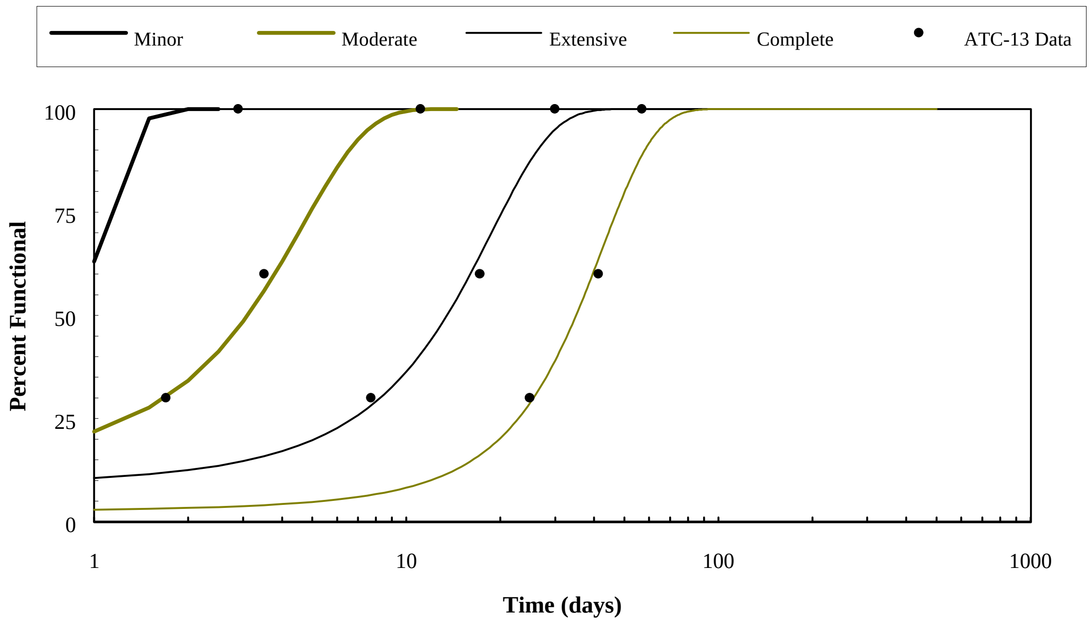


Figure 8.2: Restoration Curves for Pumping Plants (after ATC-13, 1985).

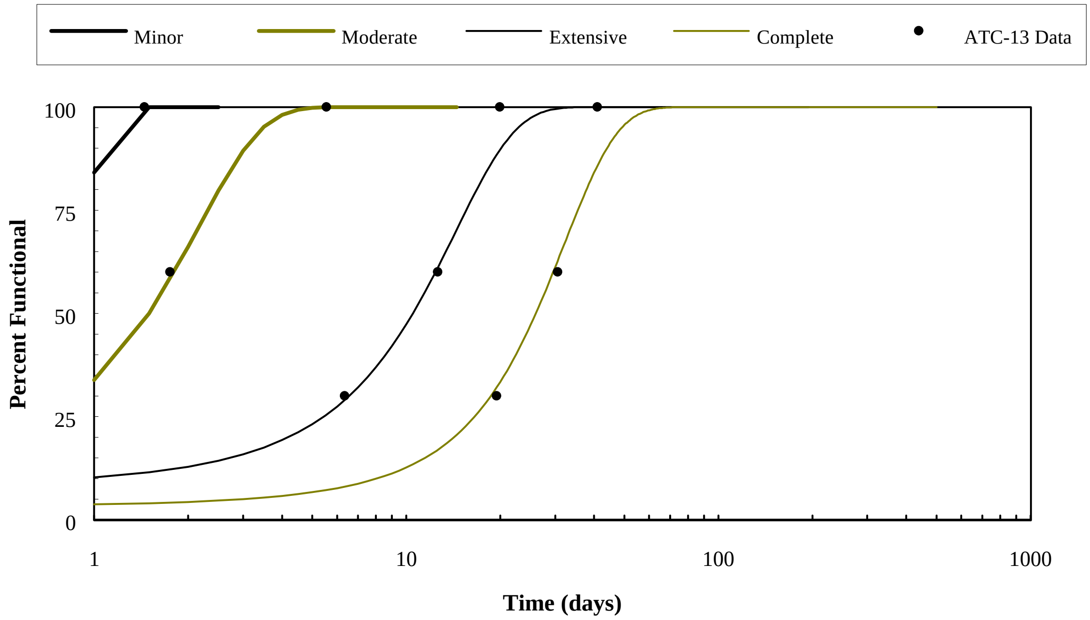


Figure 8.3: Restoration Curves for Wells (after ATC-13, 1985).

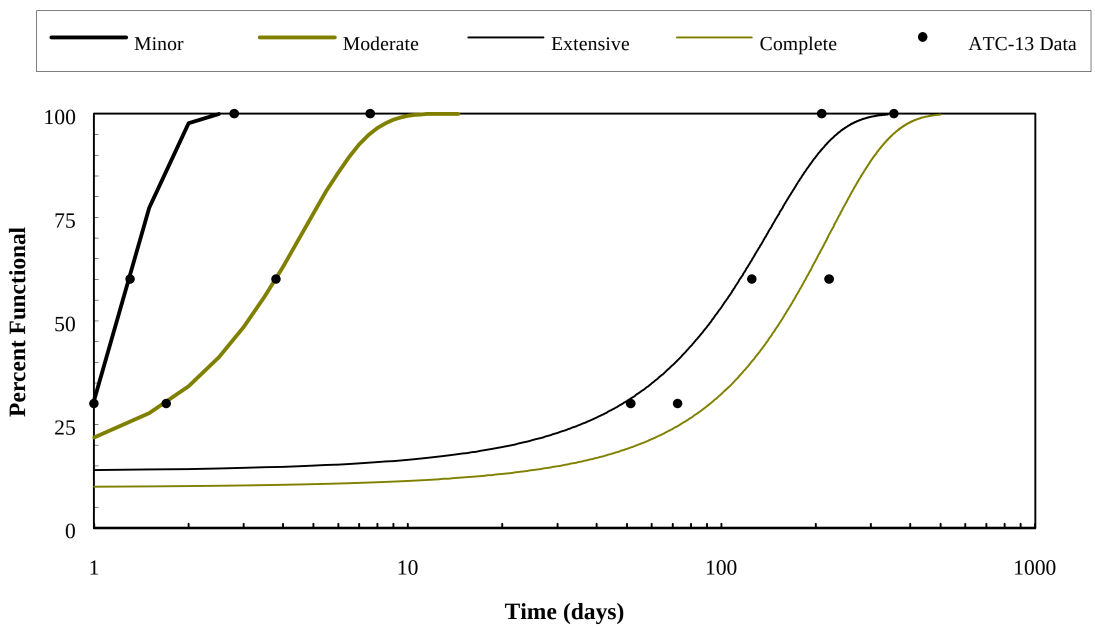


Figure 8.4: Restoration Curves for Water Storage Tanks (after ATC-13, 1985).

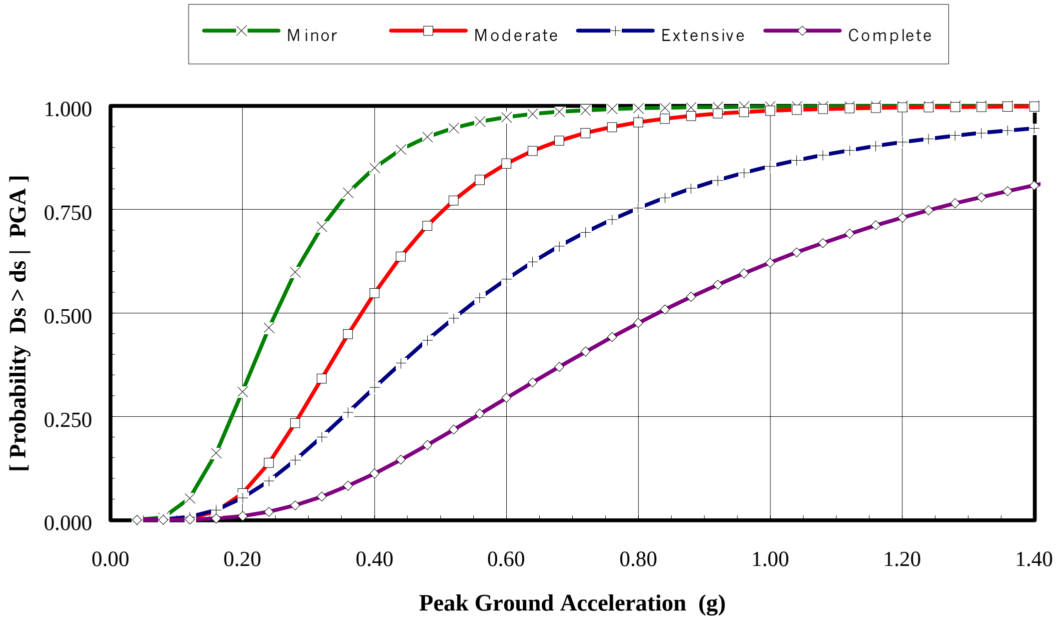


Figure 8.5: Fragility Curves for Small Water Treatment Plants with Anchored Components.

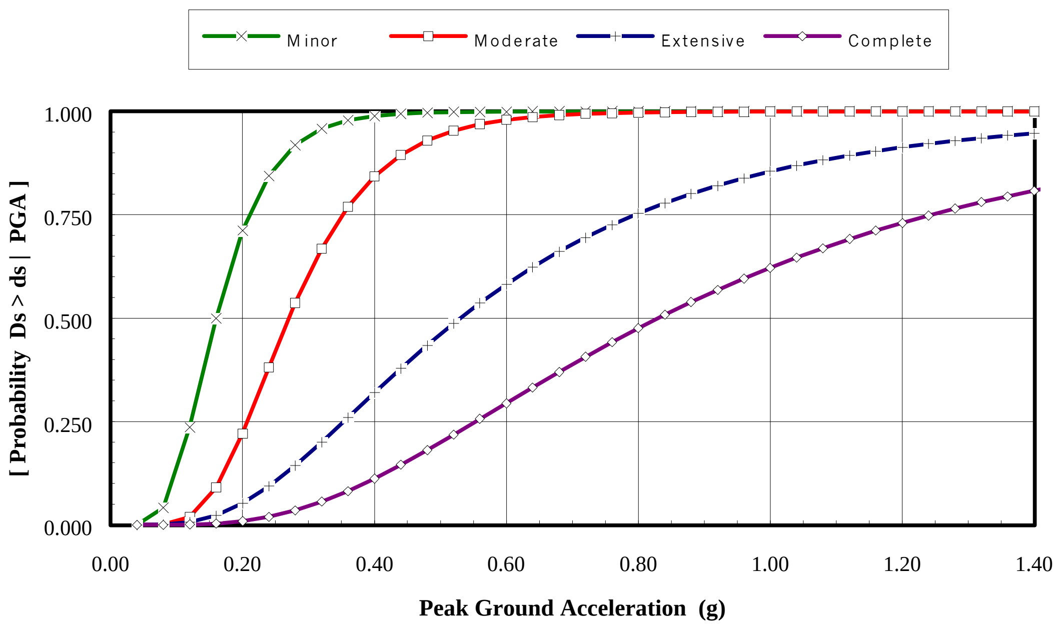


Figure 8.6: Fragility Curves for Small Water Treatment Plants with Unanchored Components.

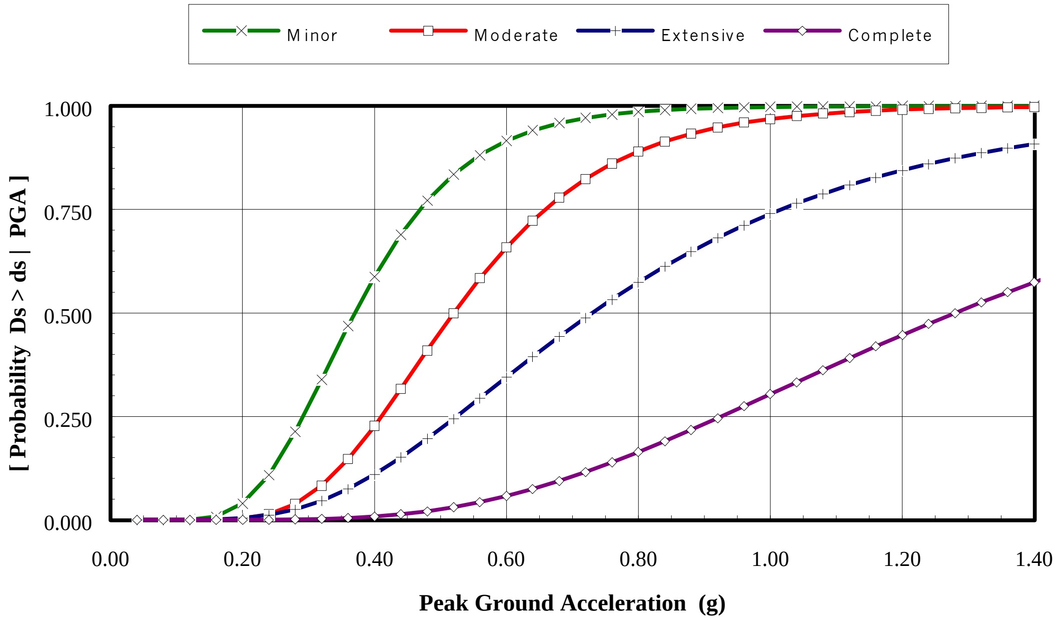


Figure 8.7: Fragility Curves for Medium Water Treatment Plants with Anchored Components.

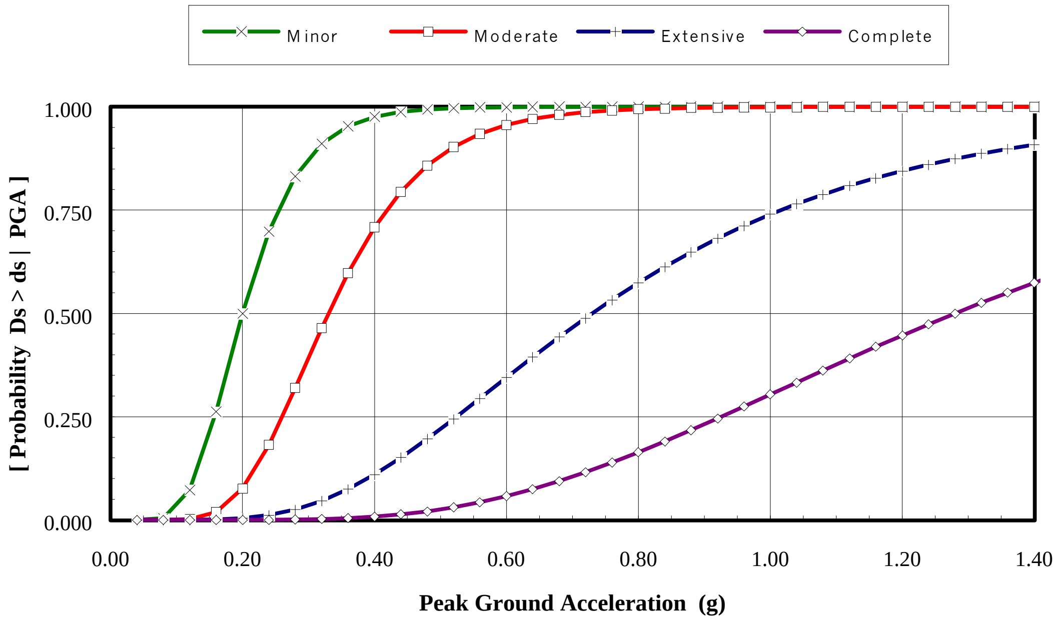


Figure 8.8: Fragility Curves for Medium Water Treatment Plants with Unanchored Components.

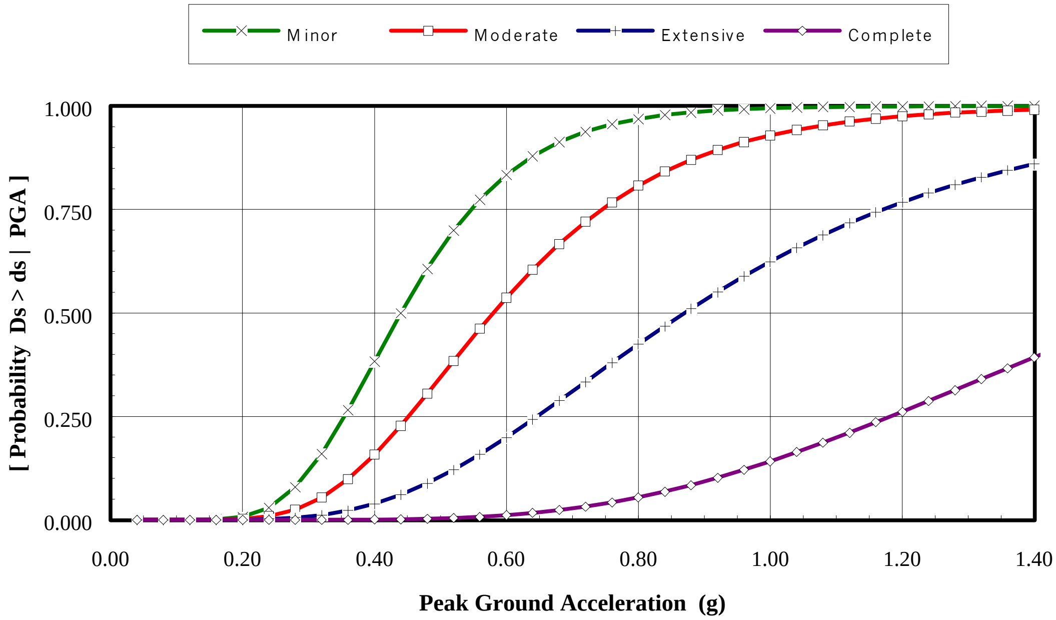


Figure 8.9: Fragility Curves for Large Water Treatment Plants with Anchored Components.

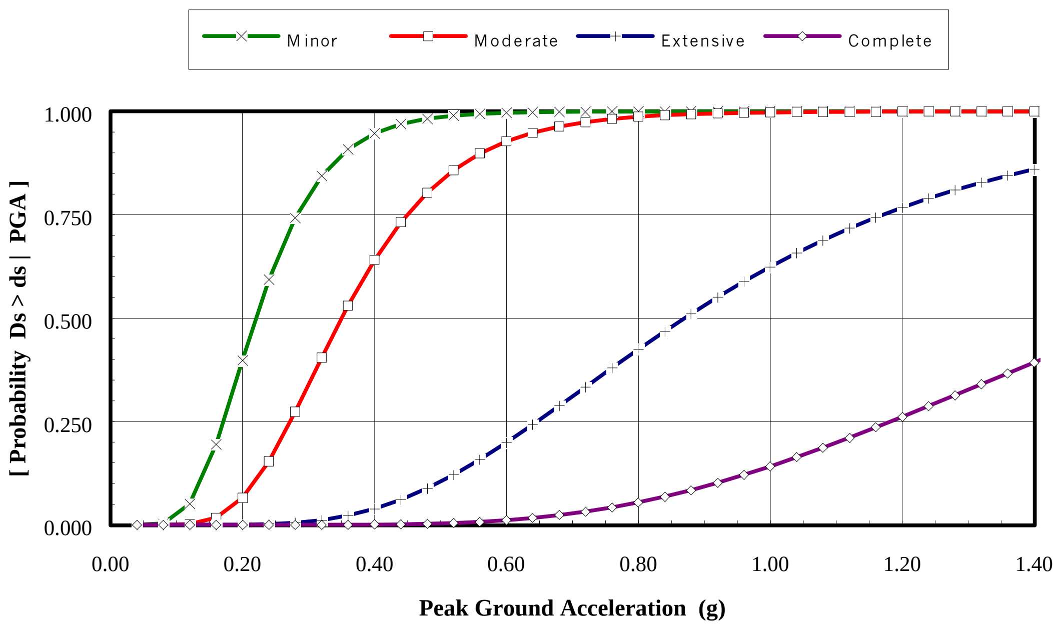


Figure 8.10: Fragility Curves for Large Water Treatment Plants with Unanchored Components.

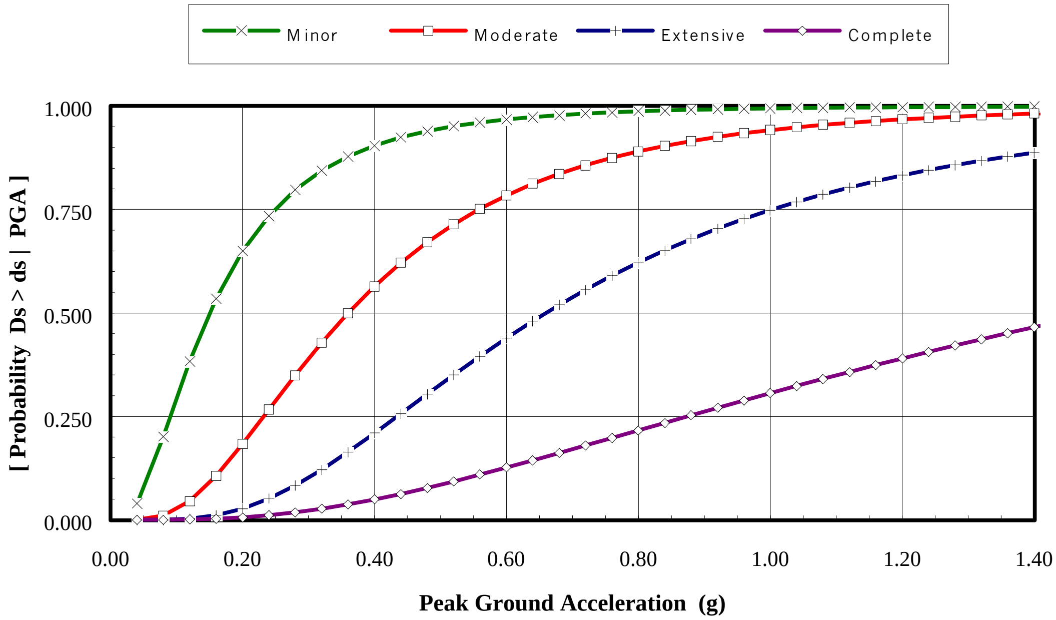


Figure 8.11: Fragility Curves for Small Pumping Plants with Anchored Components.

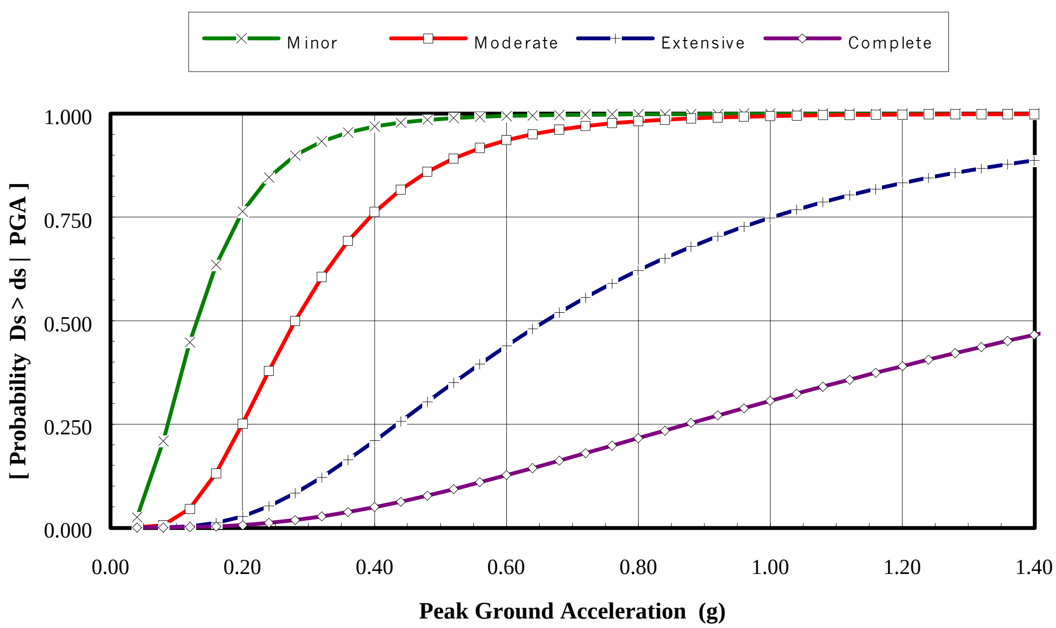


Figure 8.12: Fragility Curves for Small Pumping Plants with Unanchored Components.

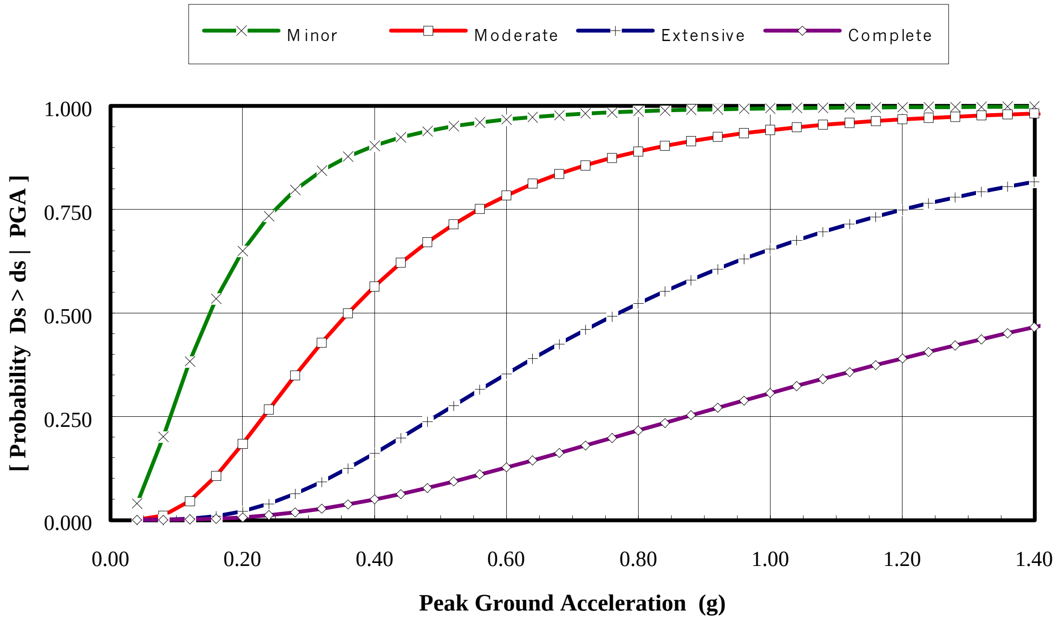


Figure 8.13: Fragility Curves for Medium/Large Pumping Plants with Anchored Components.

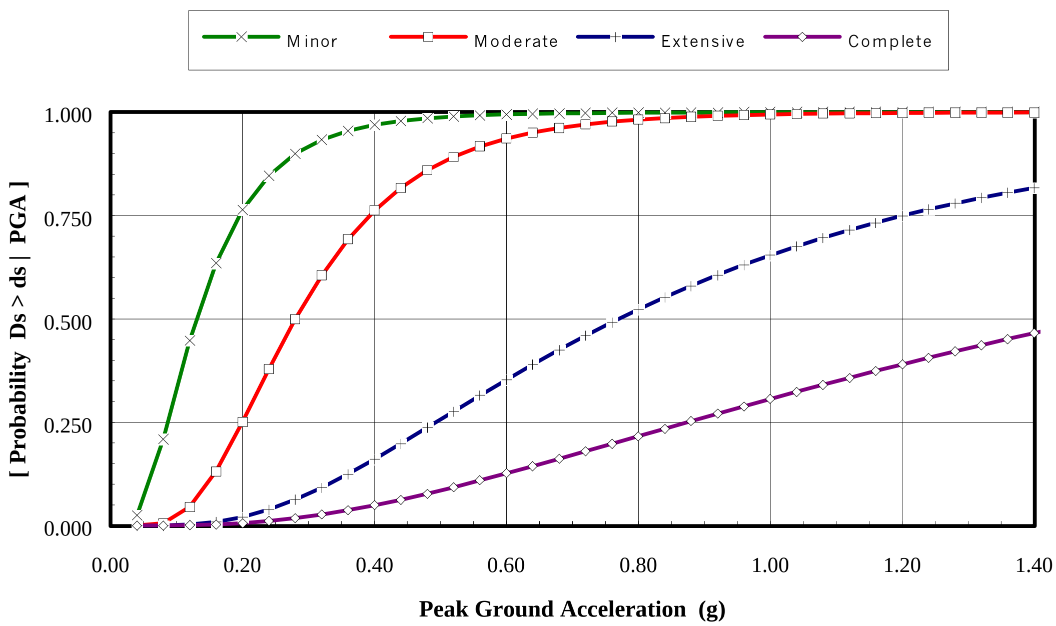


Figure 8.14: Fragility Curves for Medium/Large Pumping Plants with Anchored Components.

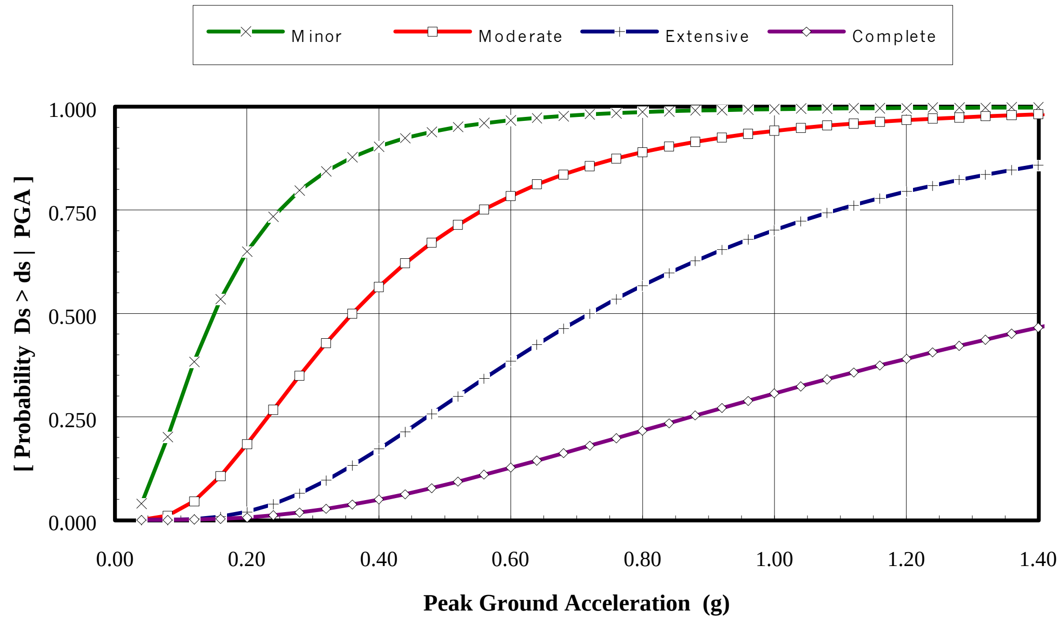


Figure 8.15: Fragility Curves for Wells

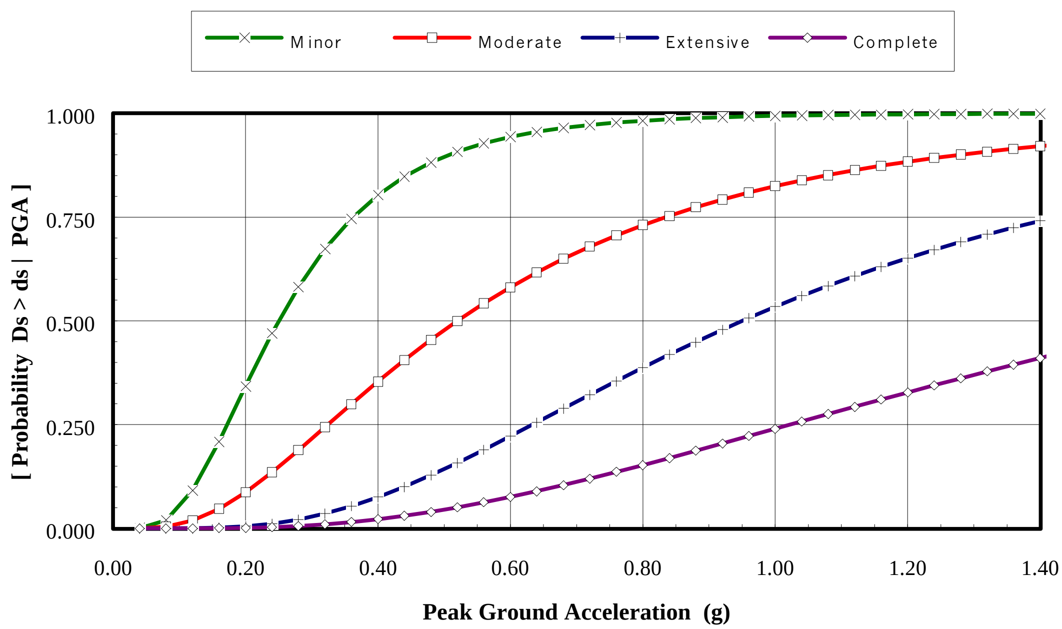


Figure 8.16: Fragility Curves for Anchored On Ground Concrete Tank.

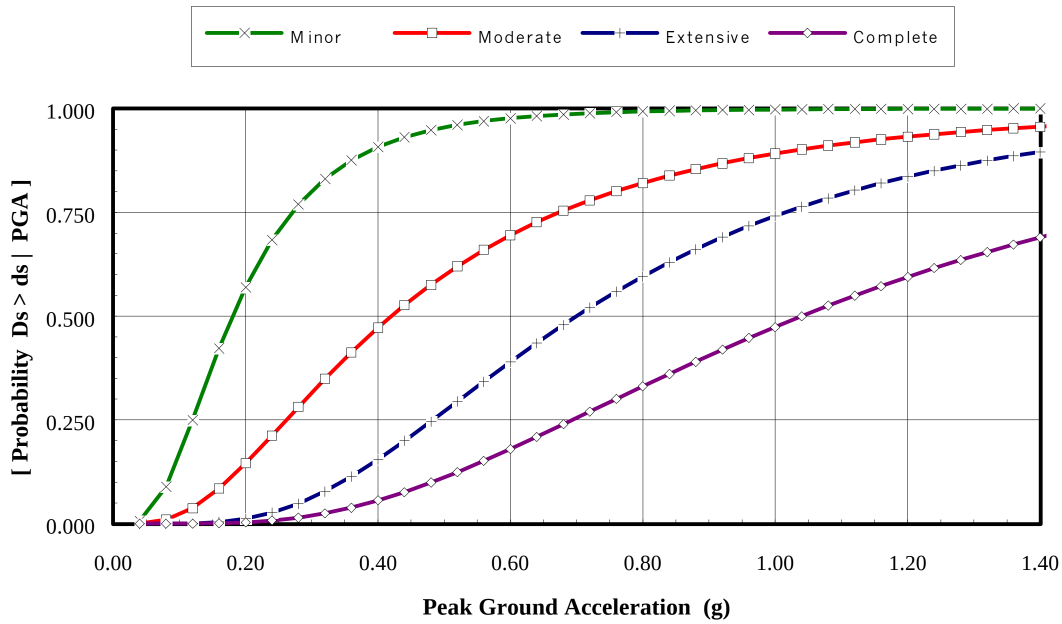


Figure 8.17: Fragility Curves for Unanchored On Ground Concrete Tank.

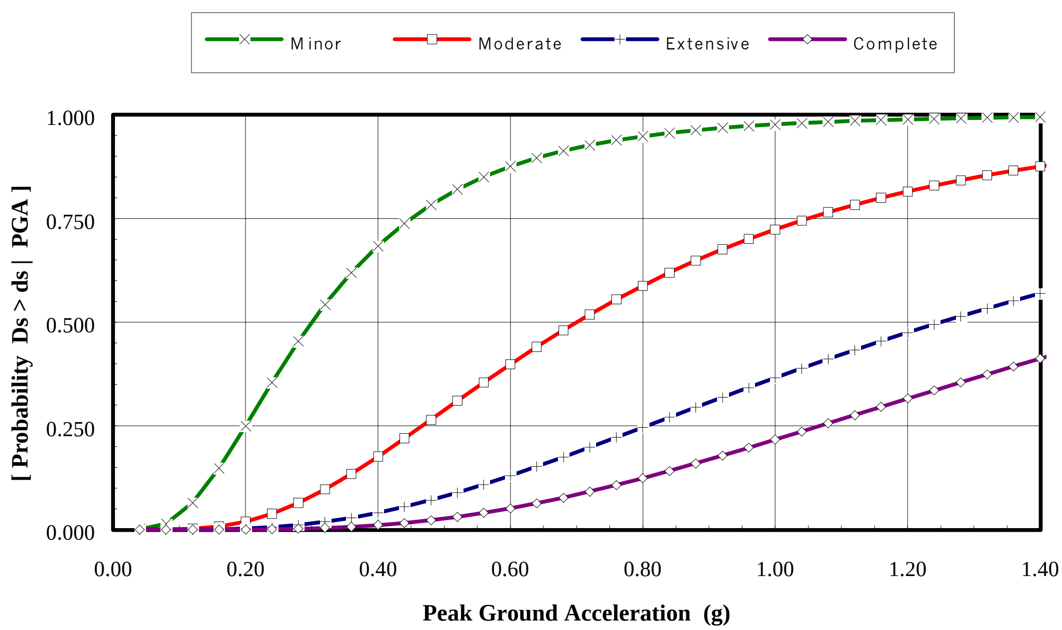


Figure 8.18: Fragility Curves for Anchored On Ground Steel Tank.

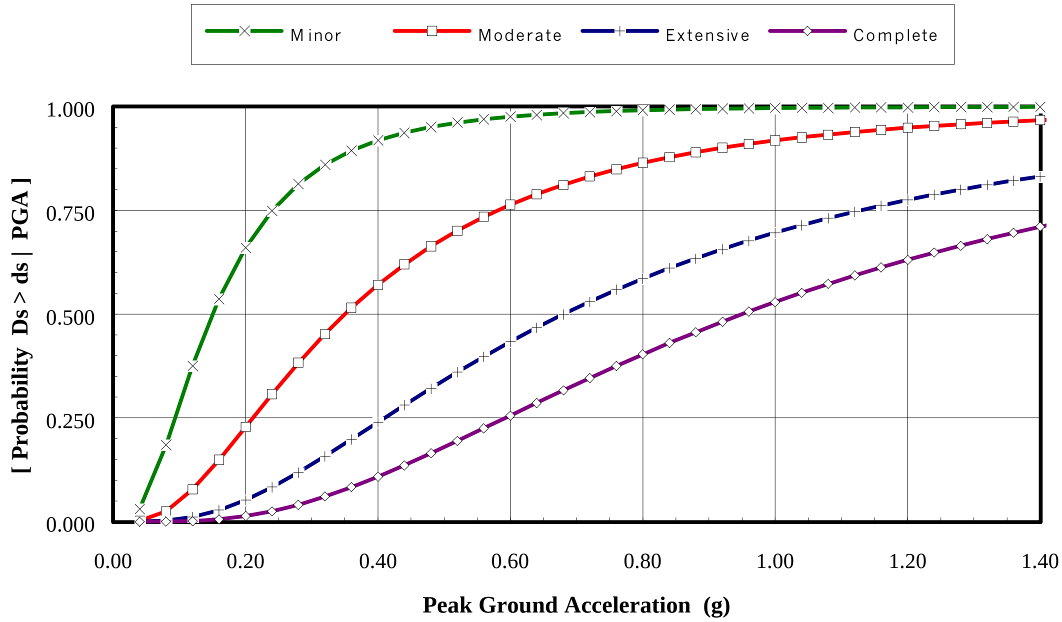


Figure 8.19: Fragility Curves for Unanchored On Ground Steel Tank.

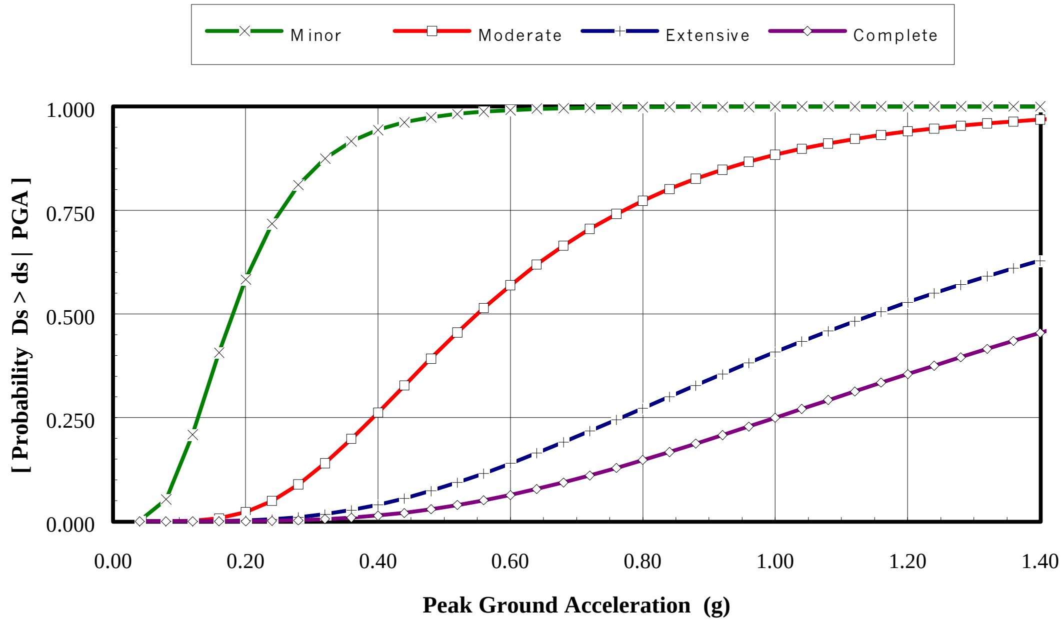


Figure 8.20: Fragility Curves for Above Ground Steel Tank.

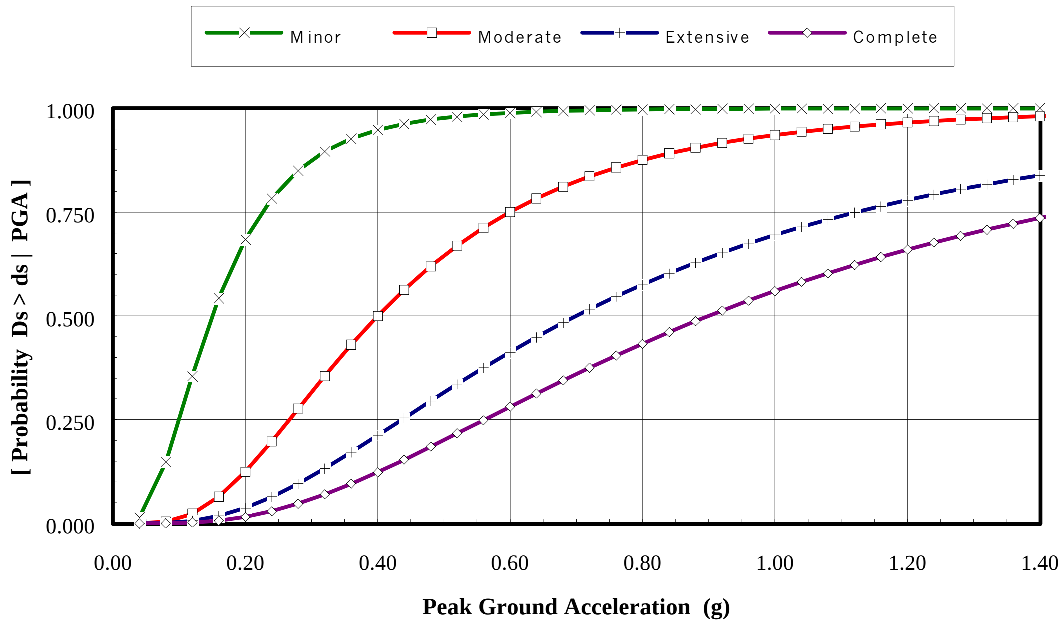


Figure 8.21: Fragility Curves for On Ground Wood Tank.

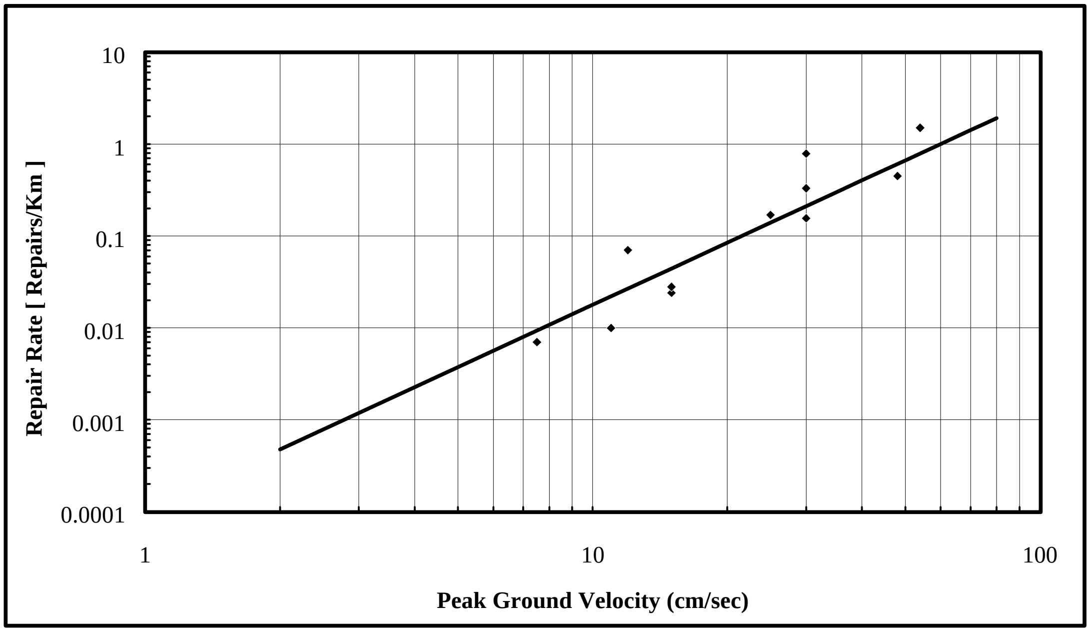


Figure 8.22.a: Ground Shaking (Wave Propagation) Damage Model for Brittle Pipes (Specifically CI, AC, RCC, and PCCP) Based on Four U.S. and Two Mexican Earthquakes (after O'Rourke and Ayala, 1993).

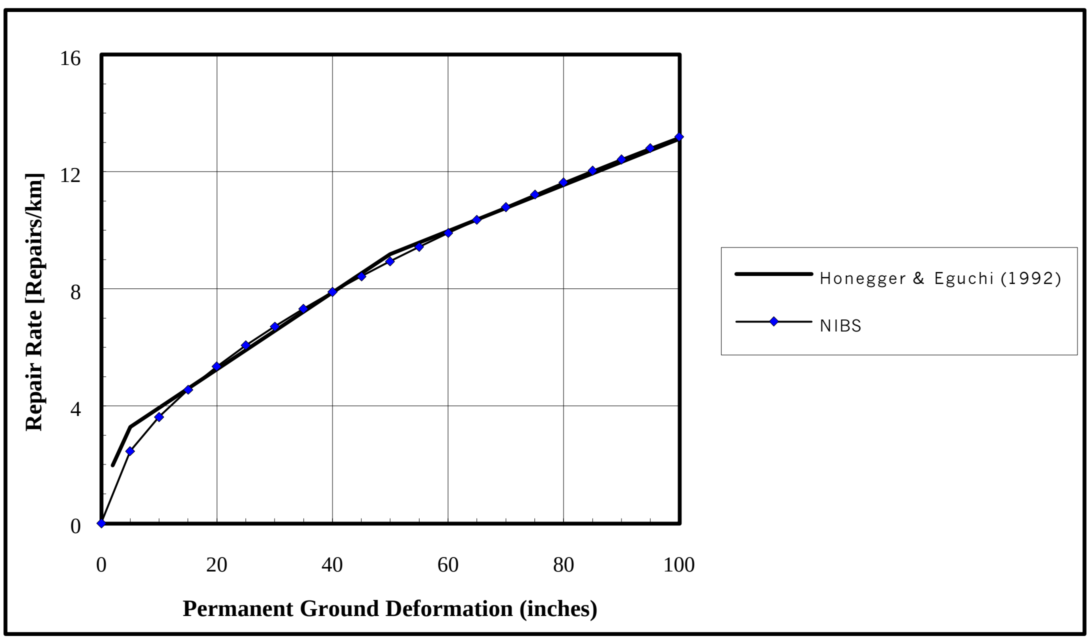


Figure 8.22.b: Ground Deformation Damage Model for Cast Iron Pipes (after Honegger and Eguchi, 1992).

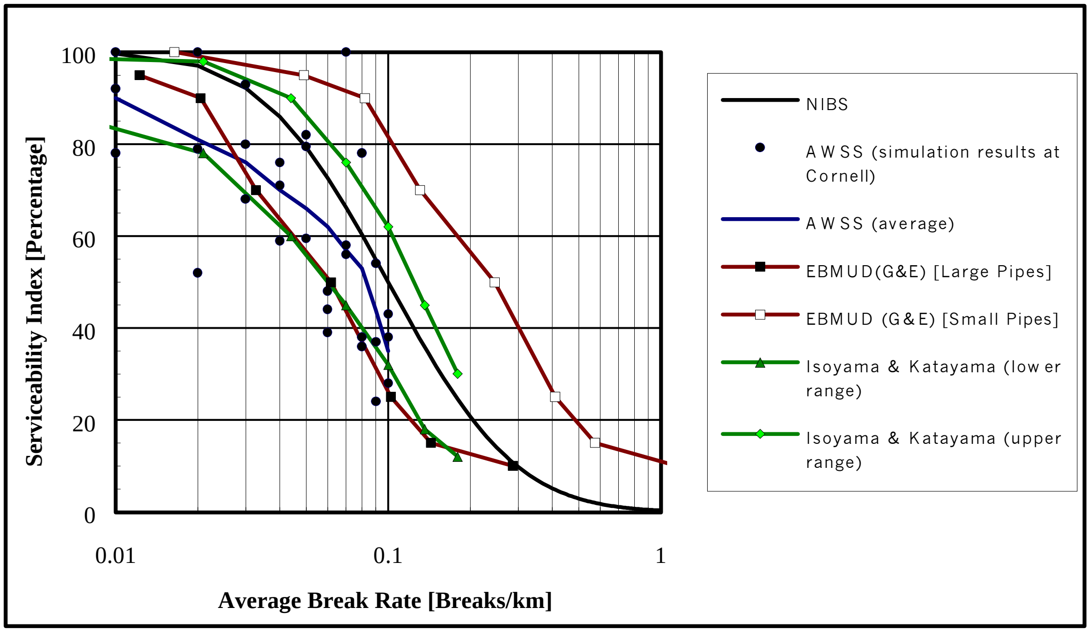


Figure 8.23: Damage Index Versus Average Break Rate for Post-Earthquake System Performance Evaluation.

8.2 Waste Water Systems

8.2.1 Introduction

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

8.2.2 Scope

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

8.2.3 Input Requirements and Output Information

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

Sewers and Interceptors

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

Waste Water Treatment Plant and Lift Stations

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

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

8.2.4 Form of Damage Functions

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

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

8.2.5 Description of Waste Water System Components

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

<u>Collection Sewers</u>

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

<u>Interceptors</u>

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.

<u>Lift Stations (LS)</u>

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

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

Waste Water Treatment Plants (WWTP)

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

8.2.6 Definitions of Damage States

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

8.2.6.1 Damage States Definitions for Components other than Sewers/Interceptors

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

Slight/Minor Damage (ds_2)

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

Moderate Damage (ds_3)

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

<u>Extensive Damage</u> (ds_4)

- **<u>For waste water treatment plants</u>**, ds_4 is defined as for WTP in potable water systems.

- **<u>For lift stations</u>**, ds_4 is defined as for pumping plants in potable water systems.

<u>Complete Damage</u> (ds_5)

- **<u>For waste water treatment plants</u>**, ds_5 is defined as for WTP in potable water systems.

- **<u>For lift stations</u>**, ds_5 is defined as for pumping plants in potable water systems.

8.2.6.2 Damage States Definitions for Sewers/Interceptors

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

8.2.7 Component Restoration Curves

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

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

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

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

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

8.2.8 Development of Damage Functions

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

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

Damage Functions for Lift Stations

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

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

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

Table 8.13: Damage Algorithms for Small Waste Water Treatment Plants

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

Table 8.14: Damage Algorithms for Medium Waste Water Treatment Plants

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

Table 8.15: Damage Algorithms for Large Waste Water Treatment Plants

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

Damage Functions for Sewers and Interceptors

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

Table 8.16: Damage Algorithms for Sewers/Interceptors

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

8.2.9 Guidance for Loss Estimation with Advanced Data and Models Analysis

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

8.2.10 References

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

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

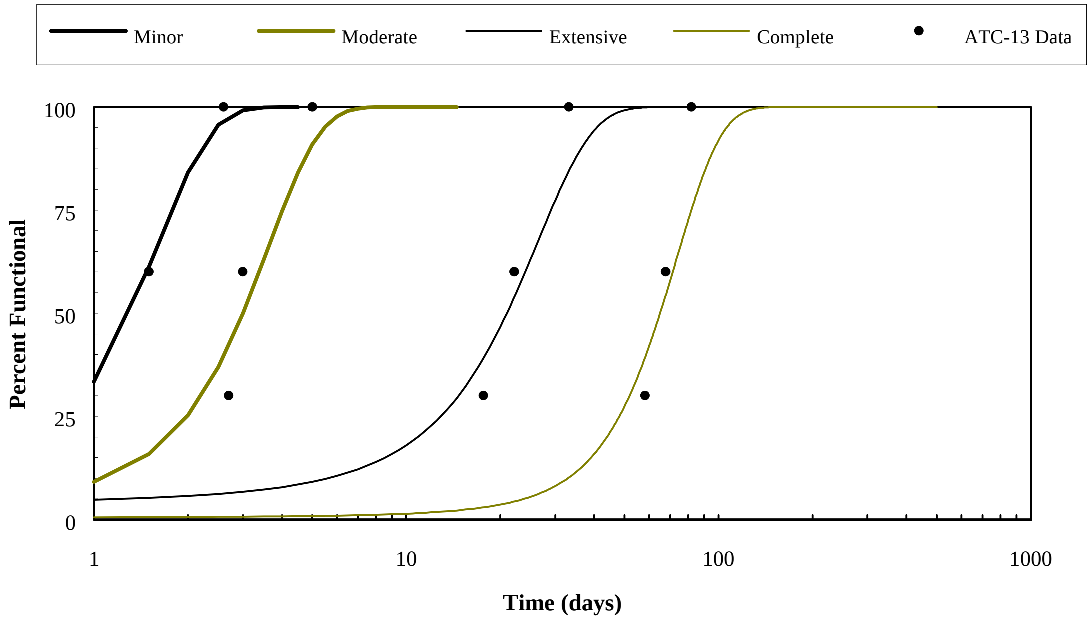


Figure 8.24: Restoration Curves for Lift Stations.

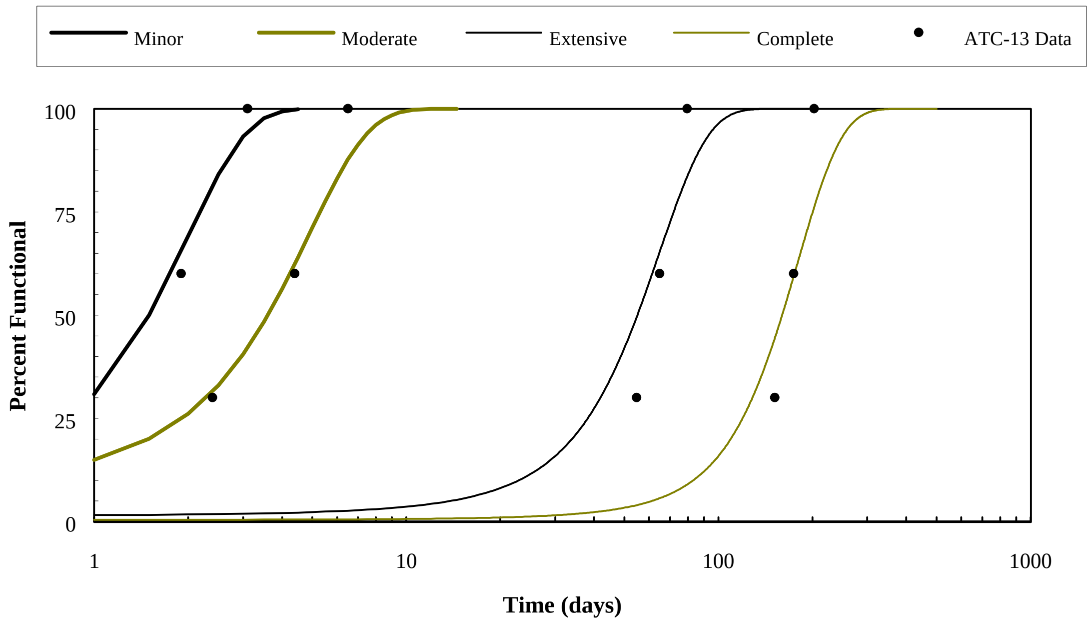


Figure 8.25: Restoration Curves for Waste Water Treatment Plants.

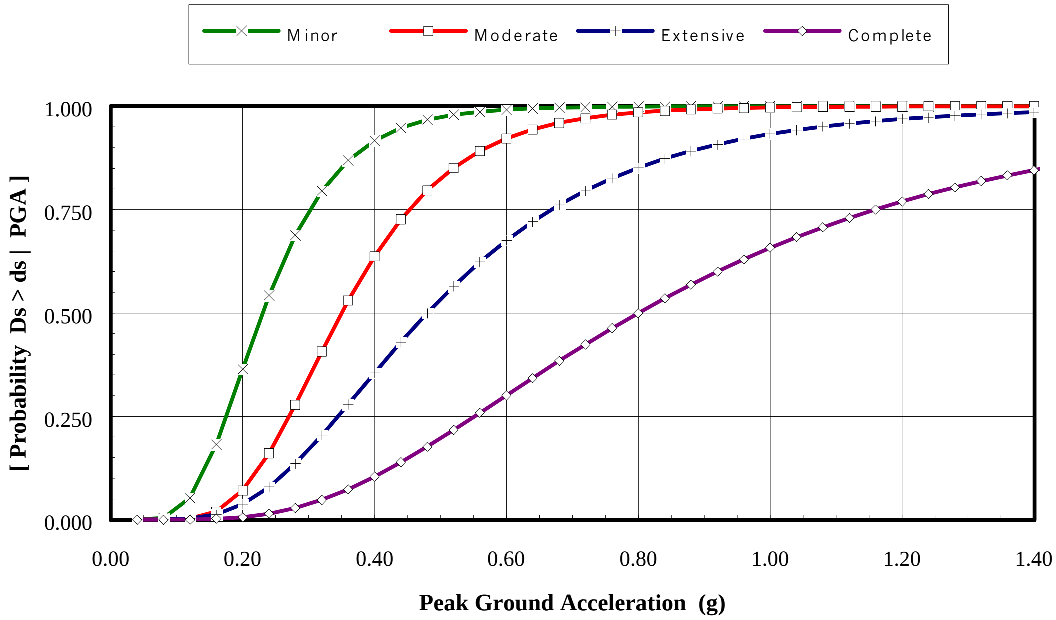


Figure 8.26: Fragility Curves for Small Waste Water Treatment Plants with Anchored Components.

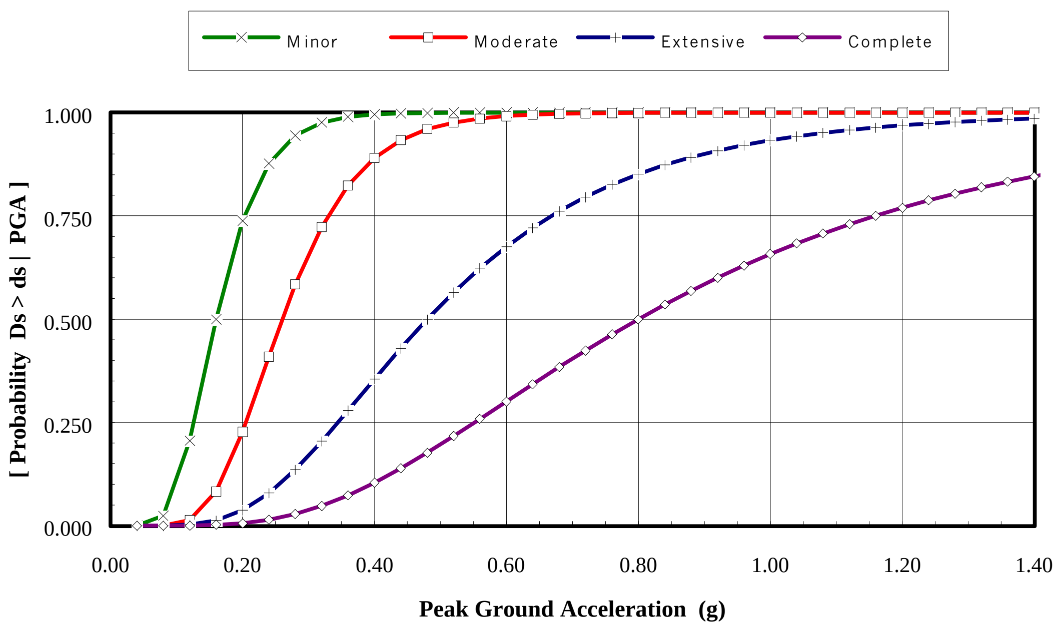


Figure 8.27: Fragility Curves for Small Waste Water Treatment Plants with Unanchored Components.

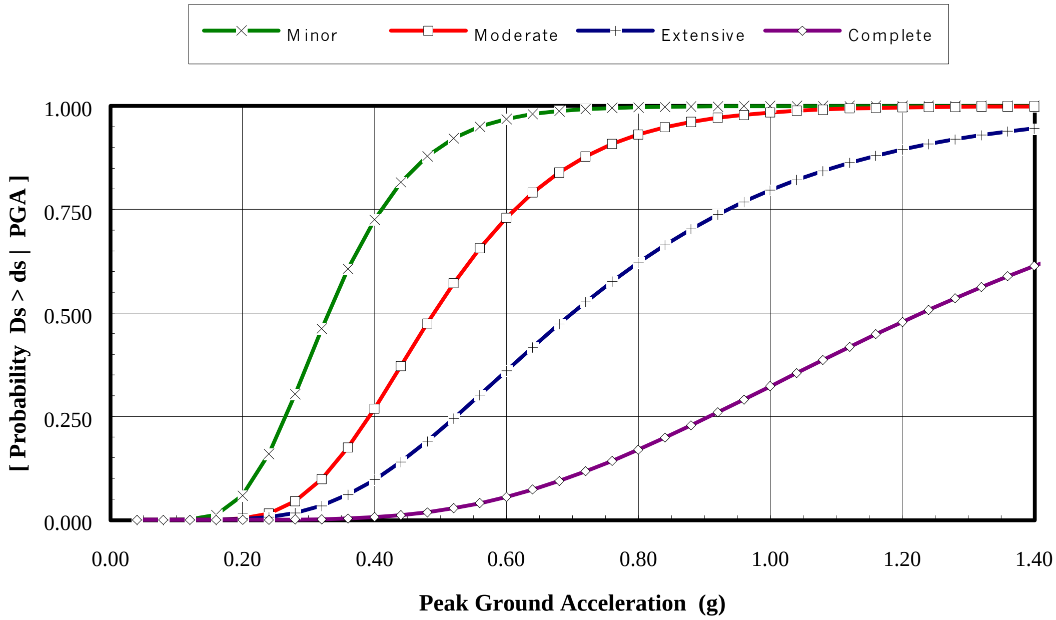


Figure 8.28: Fragility Curves for Medium Waste Water Treatment Plants with Anchored Components.

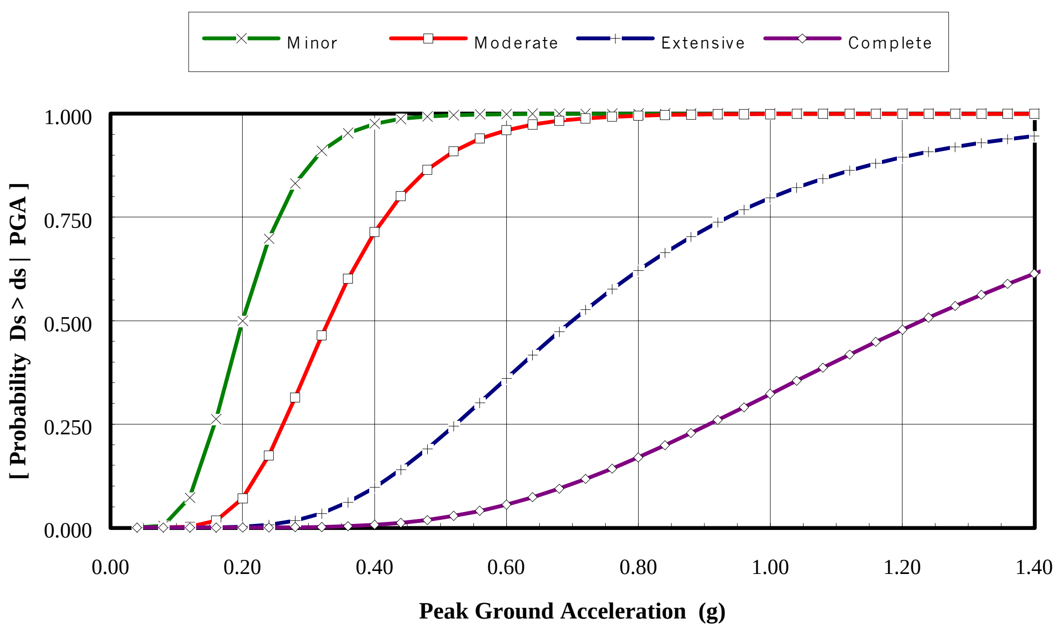


Figure 8.29: Fragility Curves for Medium Waste Water Treatment Plants with Unanchored Components.

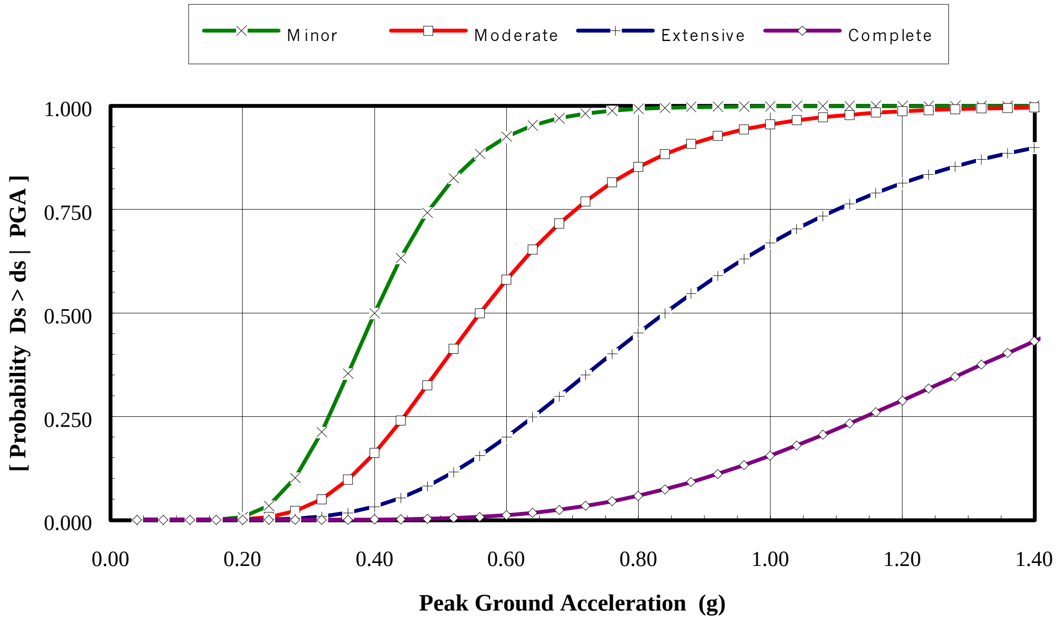


Figure 8.30: Fragility Curves for Large Waste Water Treatment Plants with Anchored Components.

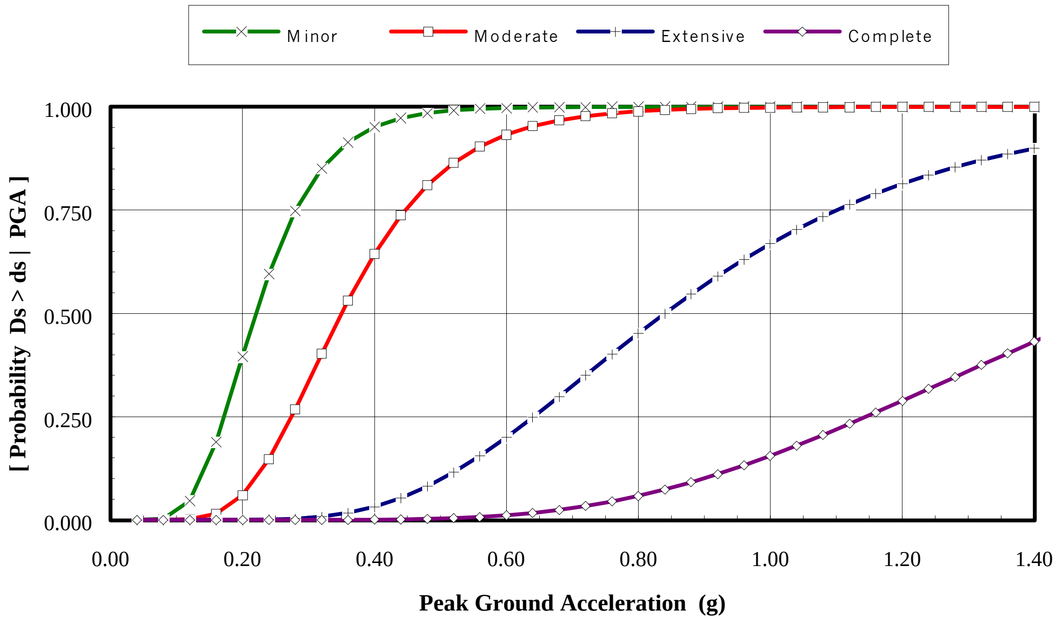


Figure 8.31: Fragility Curves for Large Waste Water Treatment Plants with Unanchored Components.

8.3 Oil Systems

8.3.1 Introduction

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

8.3.2 Scope

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

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

8.3.3 Input Requirements and Output Information

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

<u>Refineries, Pumping Plants and Tank Farms</u>

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

<u>Oil Pipelines</u>

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

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

8.3.4 Form of Damage Functions

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

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

8.3.5 Description of Oil System Components

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

Refineries (RF)

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

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

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

Oil Pipelines

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

Pumping Plants (PP)

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

Tank Farms (TF)

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

8.3.6 Definitions of Damage States

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

8.3.6.1 Damage States Definitions for Components other than Pipelines

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

Slight/Minor Damage (ds_2)

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

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

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

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

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

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

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

<u>Extensive Damage</u> (ds_4)

- **<u>For refineries</u>**, ds_4 is defined by the tanks being extensively damaged, or stacks collapsing.

- **<u>For pumping plants</u>**, ds_4 is defined by the building being extensively damaged, or pumps badly damaged.

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

<u>Complete Damage</u> (ds_5)

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

- **<u>For pumping plants</u>**, ds_5 is defined by the building being in complete damage state.

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

8.3.6.2 Damage State Definitions for Pipelines

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

8.3.7 Component Restoration Curves

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

Table 8.17.a: Restoration Functions for Oil System Components

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

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

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

8.3.8 Development of Damage Functions

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

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

Damage Functions for Refineries (due to Ground Shaking)

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

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

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

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

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

Damage Functions for Pumping Plants (due to Ground Shaking)

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

Table 8.19: Damage Algorithms for Pumping Plants

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

Damage Functions for Tank Farms (due to Ground Shaking)

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

Table 8.20: Damage Algorithms for Tank Farms

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

Damage Functions for Oil Pipelines

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

Table 8.21: Damage Algorithms for Oil Pipelines

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

8.3.9 Guidance for Loss Estimation with Advanced Data and Models

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

8.3.10 References

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

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

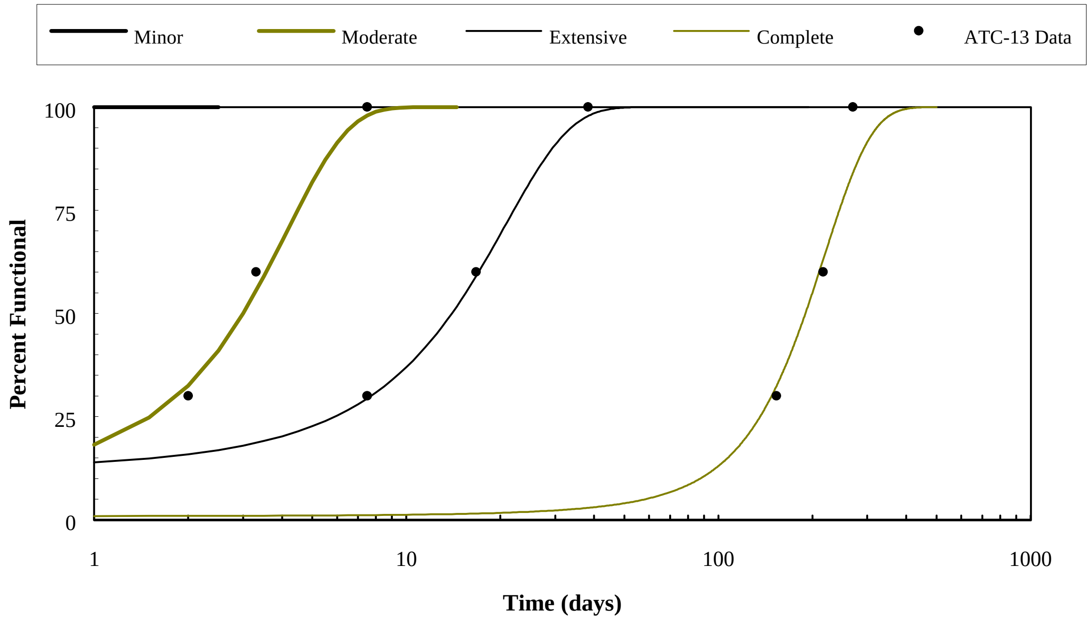


Figure 8.32: Restoration Curves for Refineries.

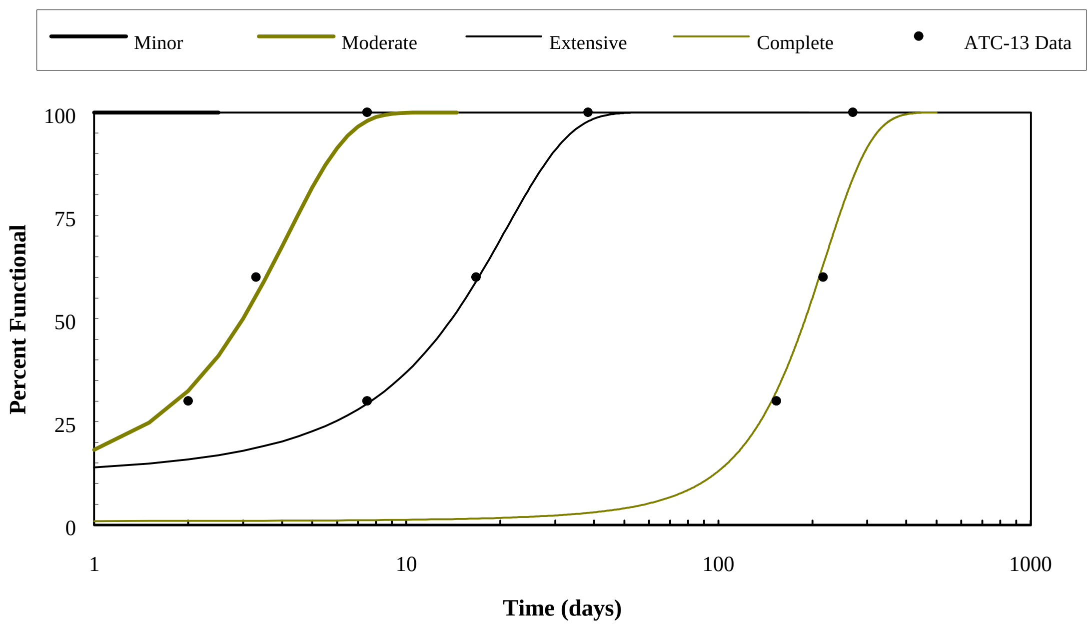


Figure 8.33: Restoration Curves for Tank Farms.

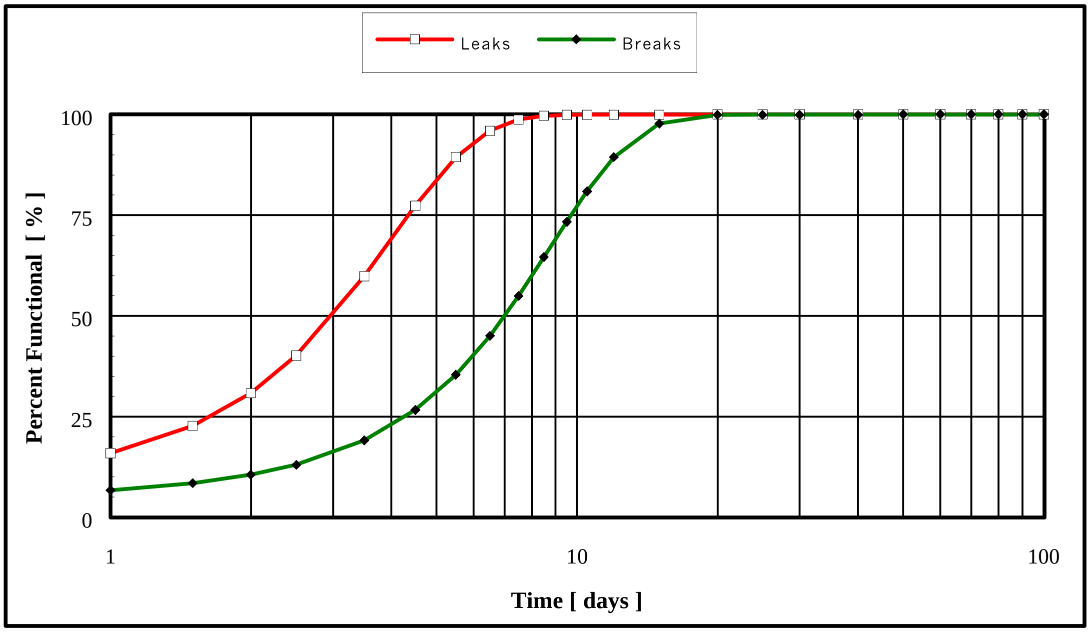


Figure 8.34: Restoration Curves for Oil Pipelines.

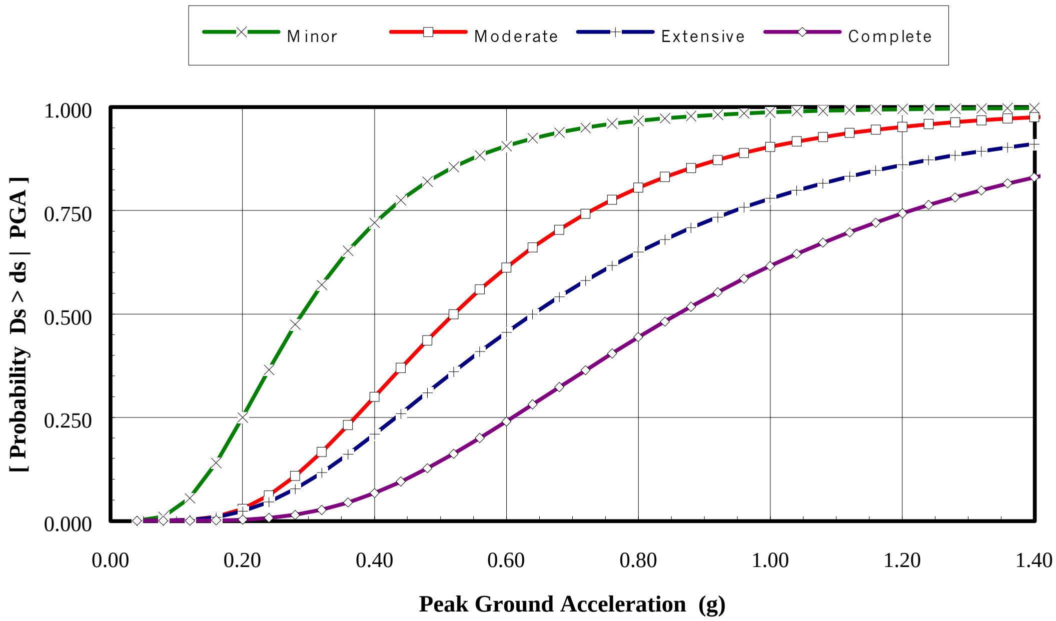


Figure 8.35: Fragility Curves for Small Refineries with Anchored Components.

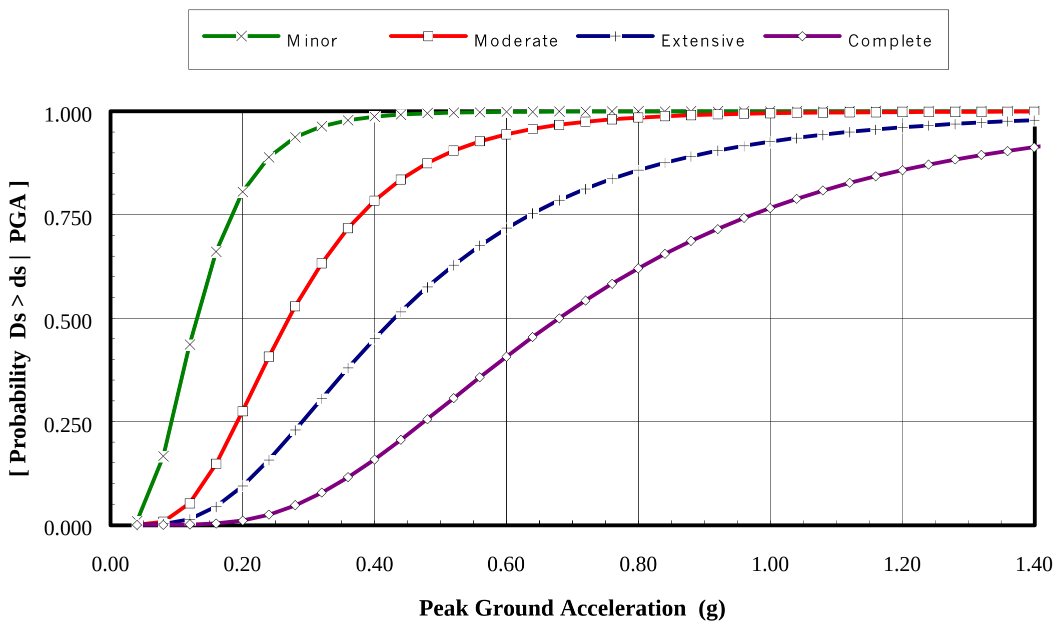


Figure 8.36: Fragility Curves for Small Refineries with Unanchored Components.

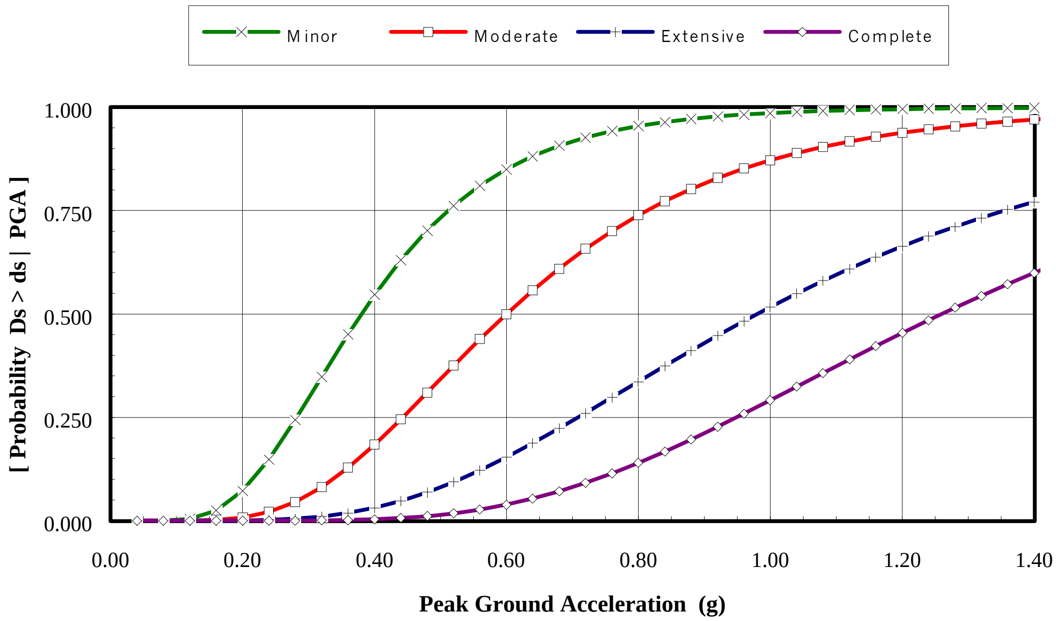


Figure 8.37: Fragility Curves for Medium/Large Refineries with Anchored Components.

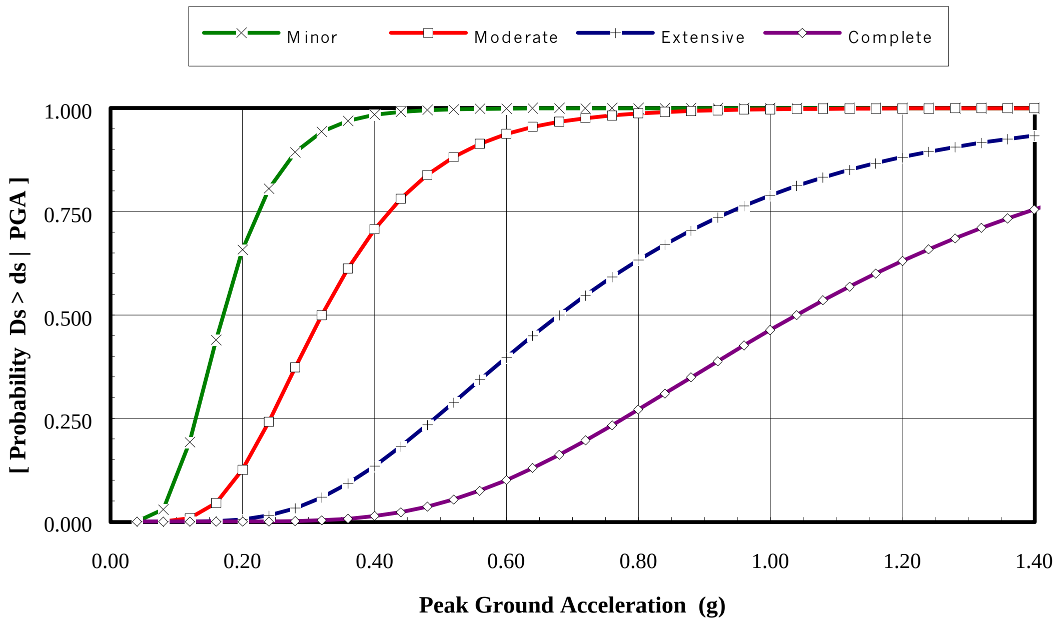


Figure 8.38: Fragility Curves for Medium/Large Refineries with Unanchored Components.

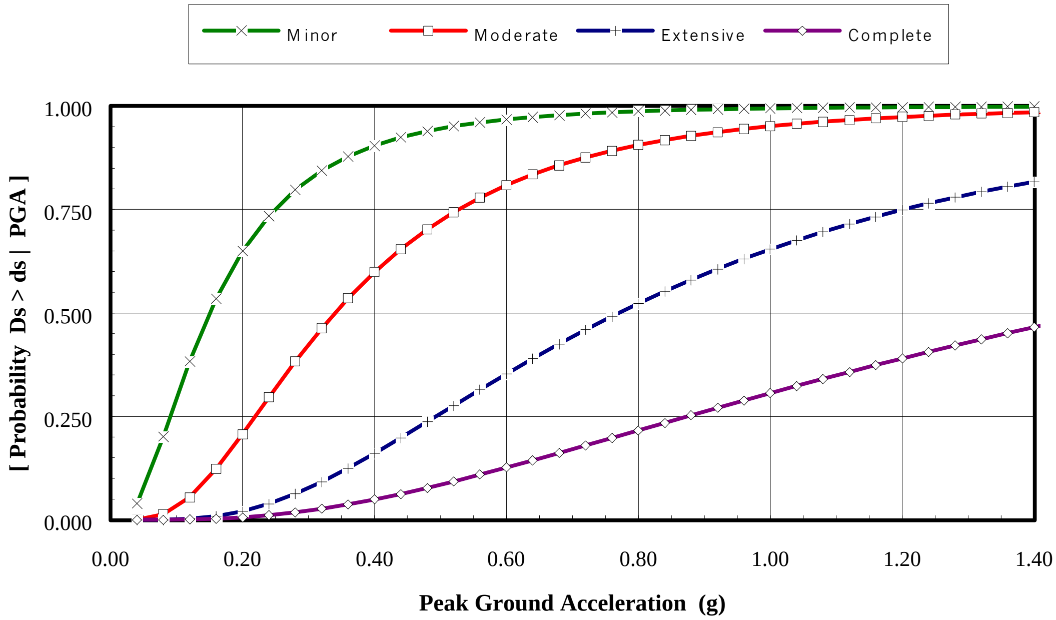


Figure 8.39: Fragility Curves for Pumping Plants with Anchored Components.

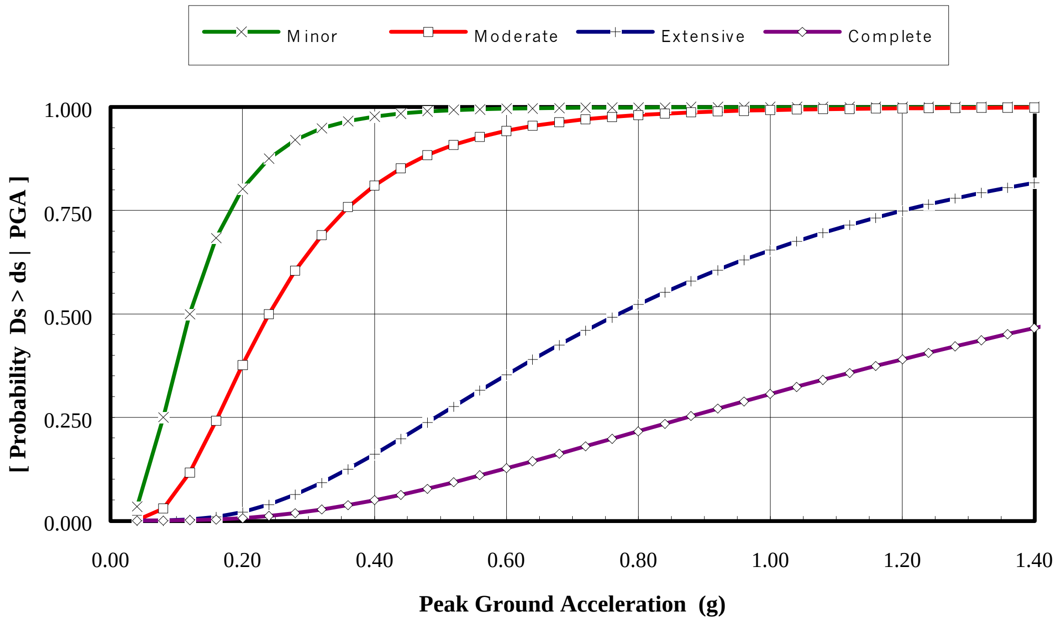


Figure 8.40: Fragility Curves for Pumping Plants with Unanchored Components.

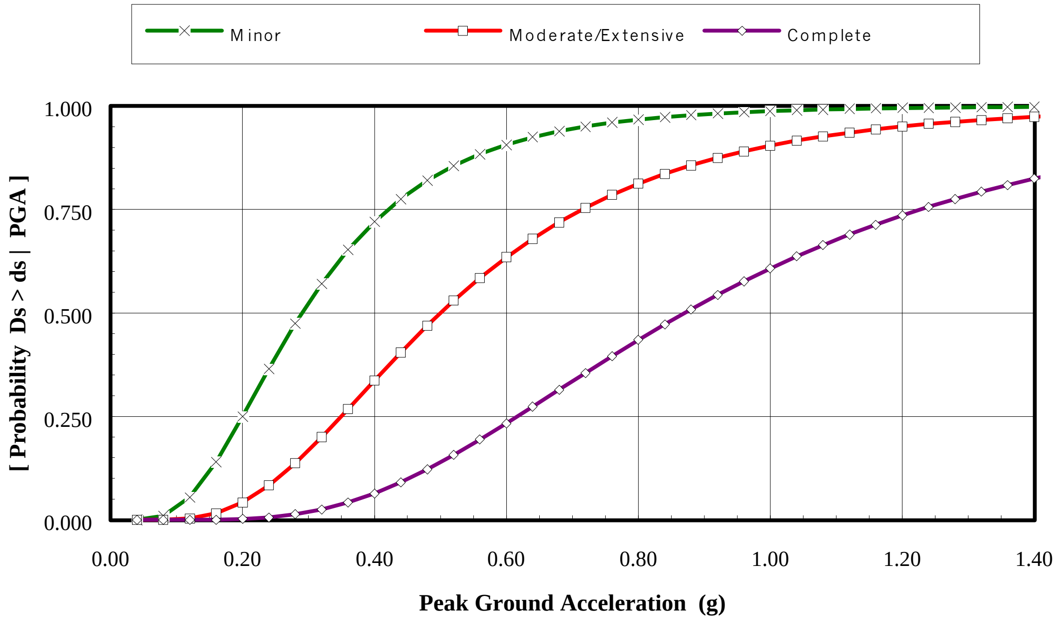


Figure 8.41: Fragility Curves for Tank Farms with Anchored Components.

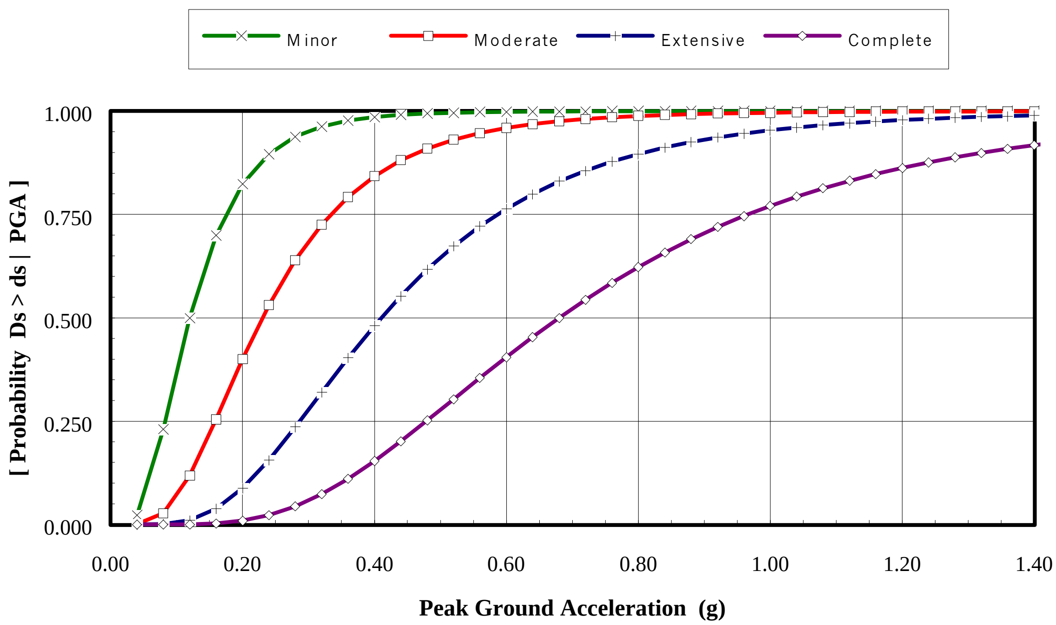


Figure 8.42: Fragility Curves for Tank Farms with Unanchored Components.

8.4 Natural Gas Systems

8.4.1 Introduction

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

8.4.2 Scope

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

8.4.3 Input Requirements and Output Information

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

Compressor Stations

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

Natural Gas Pipelines

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

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

8.4.4 Form of Damage Functions

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

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

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

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

8.4.5 Description of Natural Gas System Components

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

Compressor Stations

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

Natural Gas Pipelines

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

8.4.6 Definitions of Damage States

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

8.4.6.1 Damage States Definitions for Compressor Stations

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

Slight/Minor Damage (ds_2)

- ds_2 is defined by slight damage to building.

Moderate Damage (ds_3)

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

Extensive Damage (ds_4)

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

Complete Damage (ds_5)

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

8.4.6.2 Damage States Defintions for Pipelines

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

8.4.7 Component Restoration Curves

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

8.4.8 Development of Damage Functions

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

Damage Functions for Compressor Stations

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

Damage Functions for Pipelines

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

8.4.9 Guidance for Loss Estimation with Advanced Data and Models Analysis

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

8.4.10 References

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

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

8.5 Electric Power Systems

8.5.1 Introduction

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

8.5.2 Scope

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

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

8.5.3 Input Requirements and Output Information

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

<u>Substations</u>

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

<u>Distribution Circuits</u>

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

<u>Generation Plants</u>

- Longitude and latitude of facility
- PGA

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

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

8.5.4 Form of Damage Functions

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

8.5.5 Description of Electric Power System Components

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

Substations

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

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

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

Distribution Circuits

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

Generation Plants

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

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

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

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

8.5.6 Definitions of Damage States

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

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

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

Slight/Minor Damage (ds_2)

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

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

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

Moderate Damage (ds_3)

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

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

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

Extensive Damage (ds_4)

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

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

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

Complete Damage (ds_5)

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

8.5.7 Component Restoration Curves

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

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

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

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

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

8.5.8 Development of Damage Functions

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

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

<u>PGA Related Damage Functions for Electric Power Substations</u>

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

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

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

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

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

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

PGA Related Damage Functions for Distribution Circuits

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

Table 8.25: Damage Algorithms for Distribution Circuits

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

PGA Related Damage Functions for Generation Plants

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

Table 8.26: Damage Algorithms for Small Generation Facilities

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

Table 8.27: Damage Algorithms for Medium/Large Generation Facilities

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

8.5.9 Power Outage and Performance Evaluation for Electric Power Systems

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

Example

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

Table 8.28: Electric Power System Performance Example Parameters

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

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

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

At Substation 1,

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

At substation 2,

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

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

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

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

At substation # 1,

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

= 91.8 %

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

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

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

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

Table 8.29: Generic Damage Algorithm for Electric Power System

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

8.5.10 Guidance for Loss Estimation with Advanced Data and Models Analysis

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

8.5.11 References

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

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

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

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

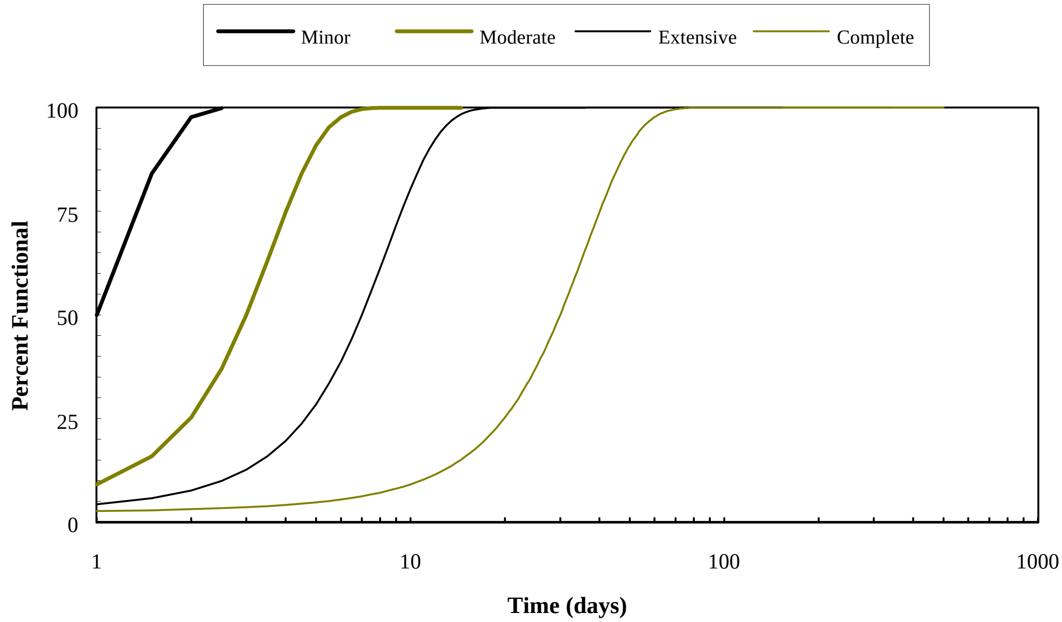


Figure 8.43: Restoration Curves for Electric Substations.

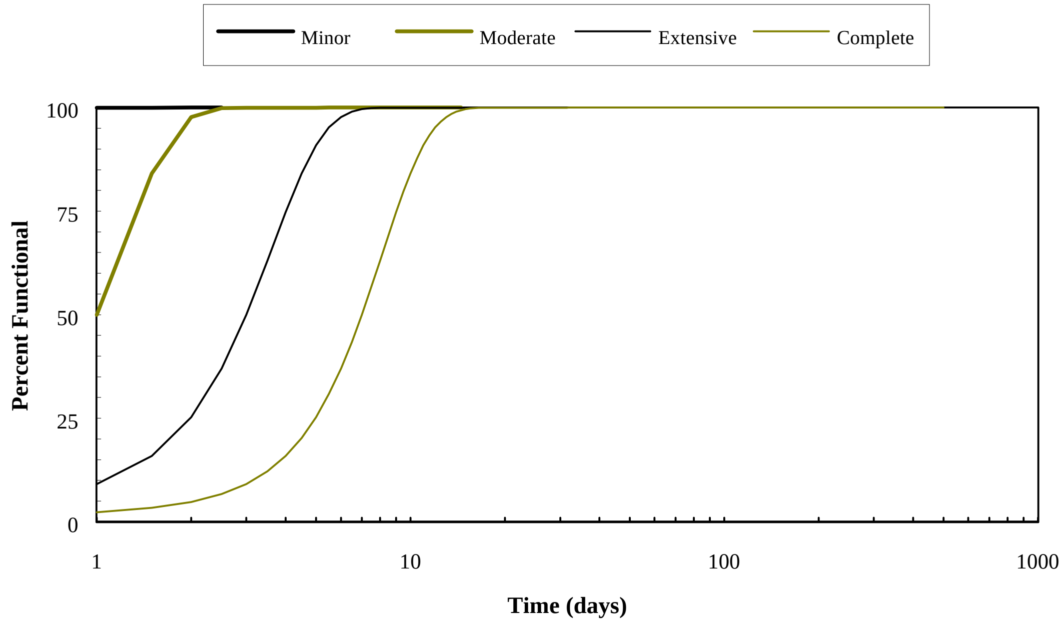


Figure 8.44: Restoration Curves for Distribution Circuits.

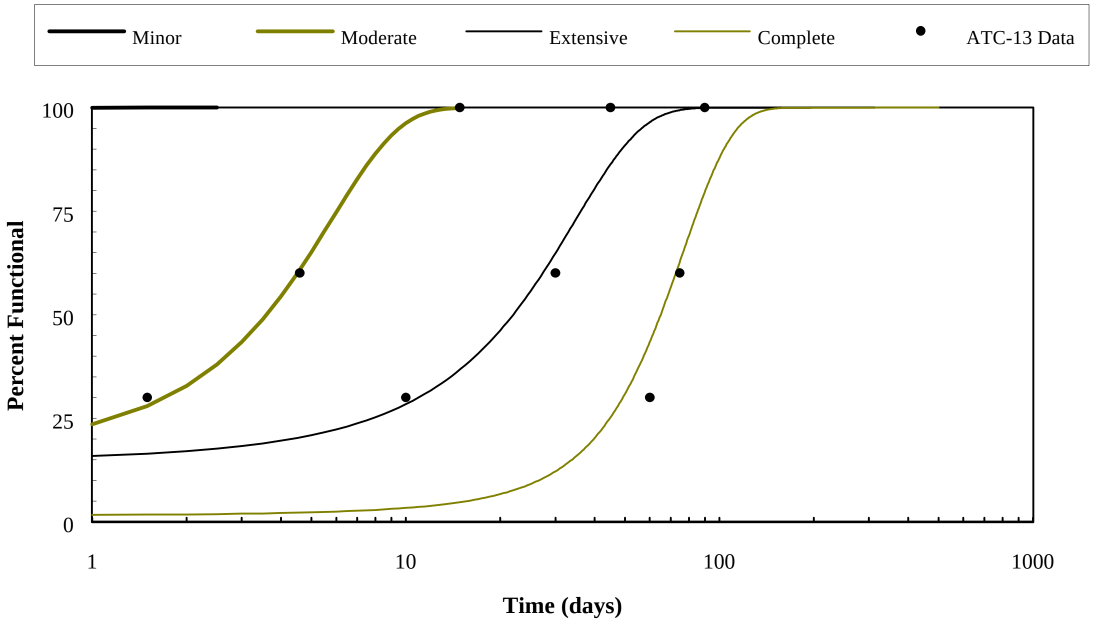


Figure 8.45: Restoration Curves for Generation Facilities.

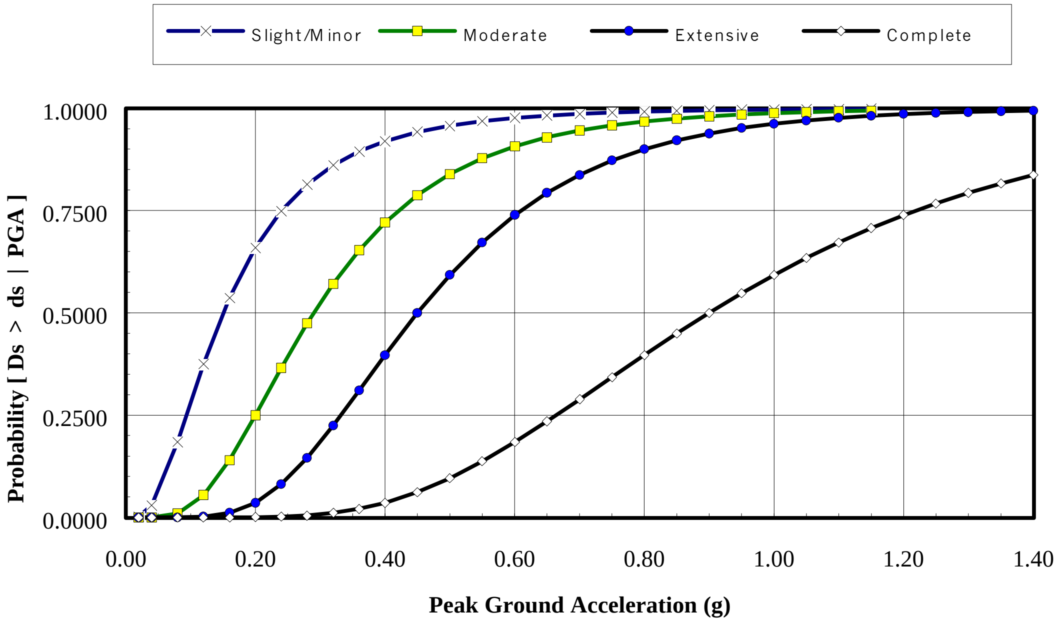


Figure 8.46: Fragility Curves for Low voltage Substations with Seismic Components.

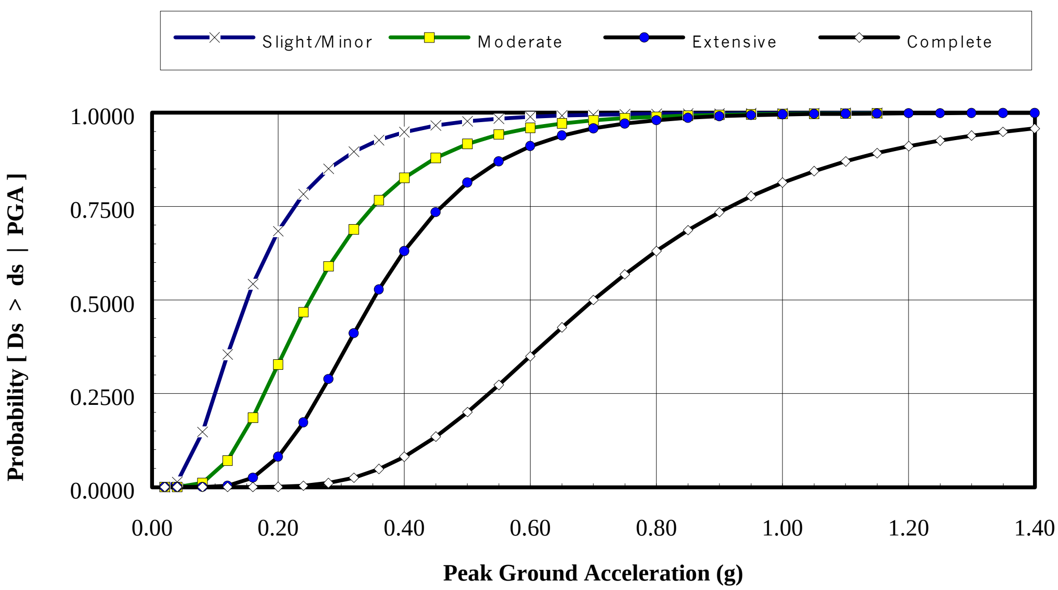


Figure 8.47: Fragility Curves for Medium Voltage Substations with Seismic Components.

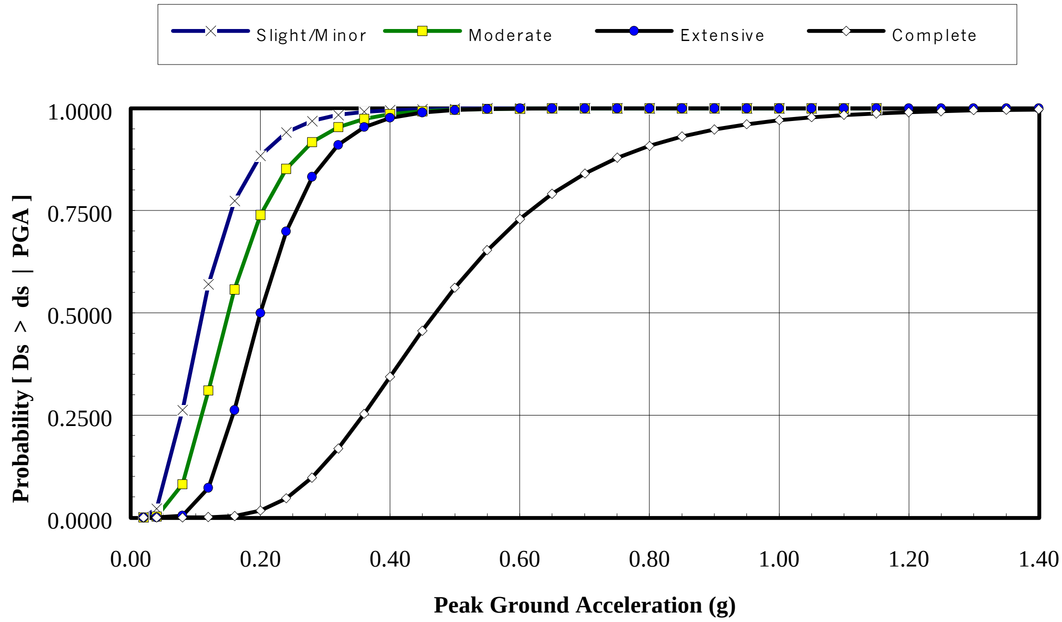


Figure 8.48: Fragility Curves for High Voltage Substations with Seismic Components.

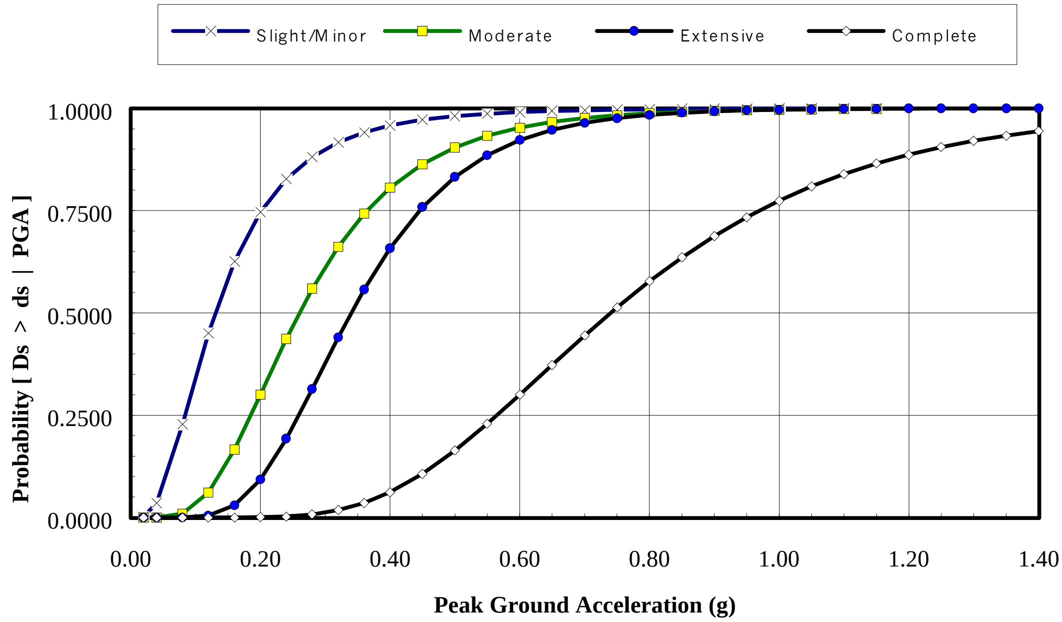


Figure 8.49: Fragility Curves for Low Voltage Substations with Standard Components.

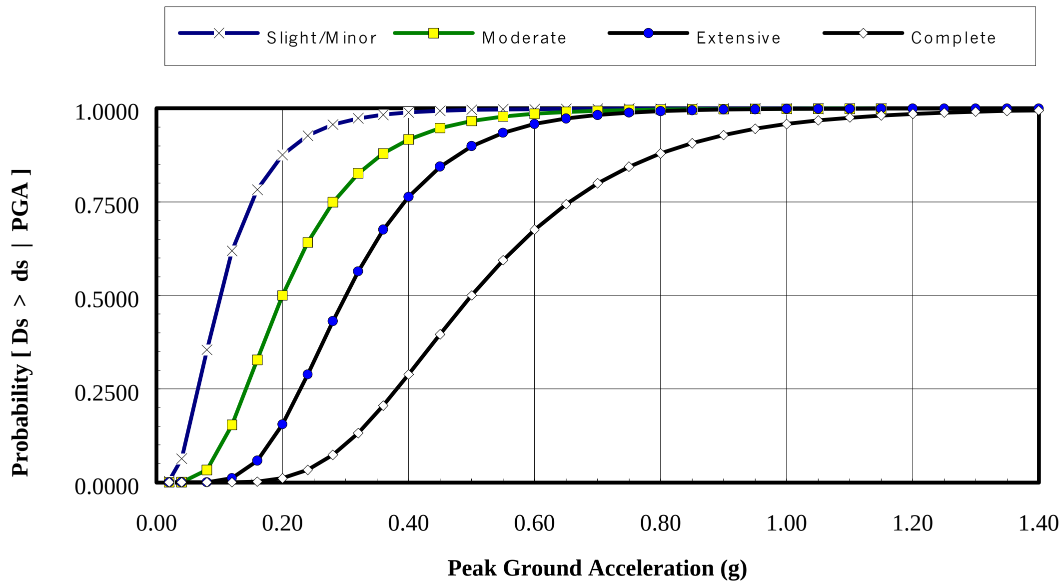


Figure 8.50: Fragility Curves for Medium Voltage Substations with Standard Components.

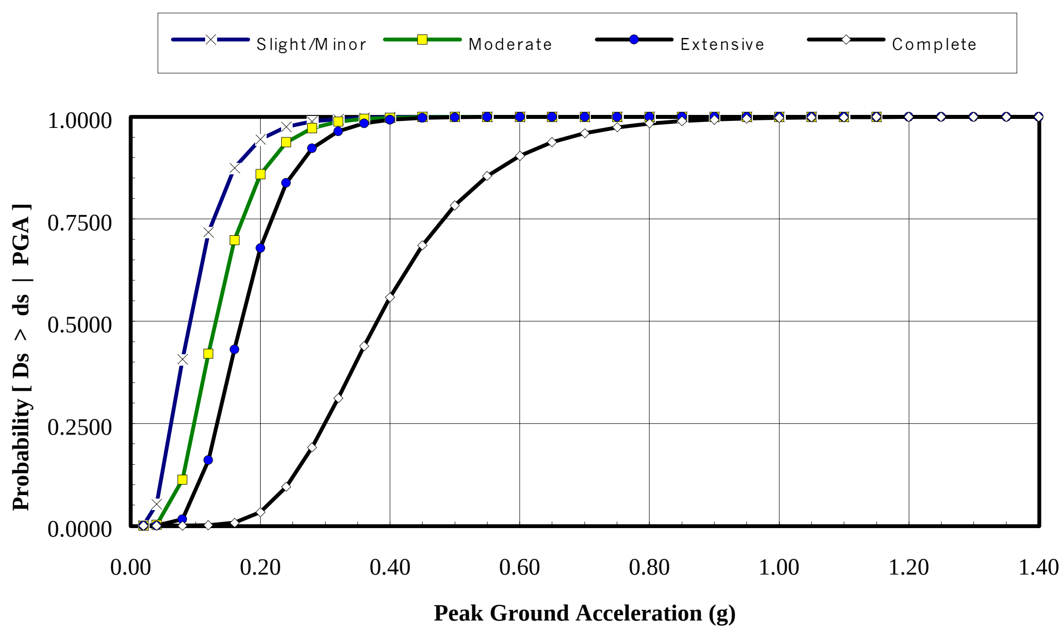


Figure 8.51: Fragility Curves for High Voltage Substations with Standard Components.

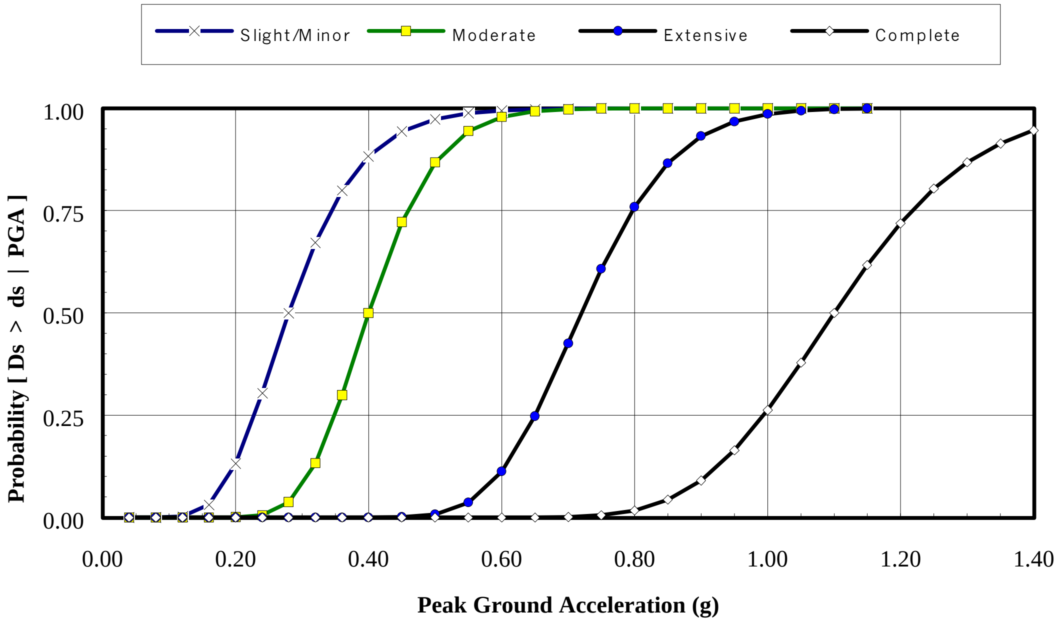


Figure 8.52: Fragility Curves for Seismic Distribution Circuits.

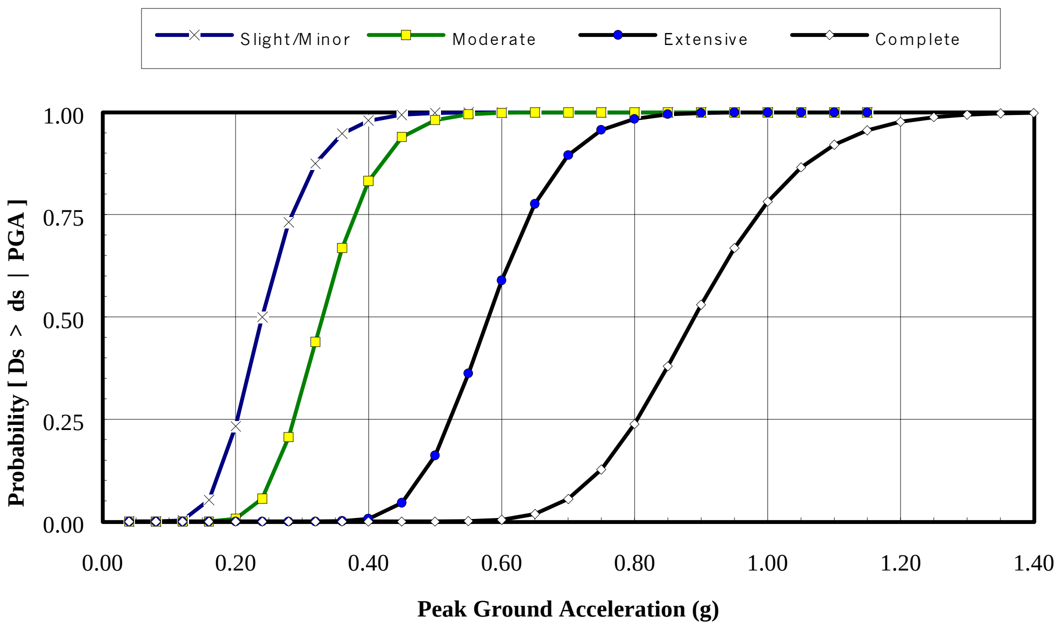


Figure 8.53: Fragility Curves for Standard Distribution Circuits.

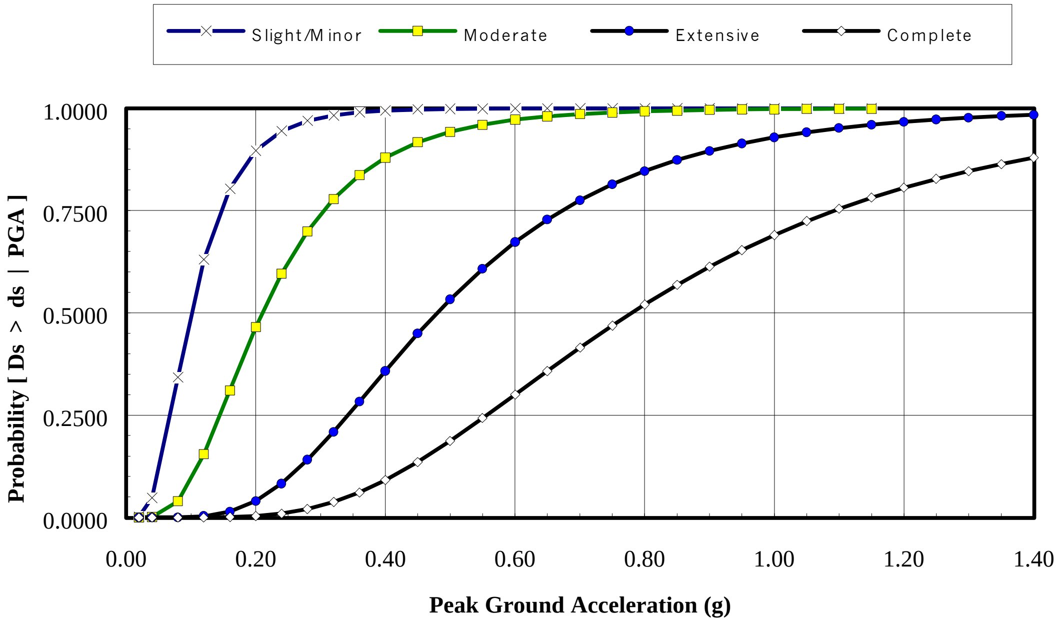


Figure 8.54: Fragility Curves for Small Generation Facilities with Anchored Components.

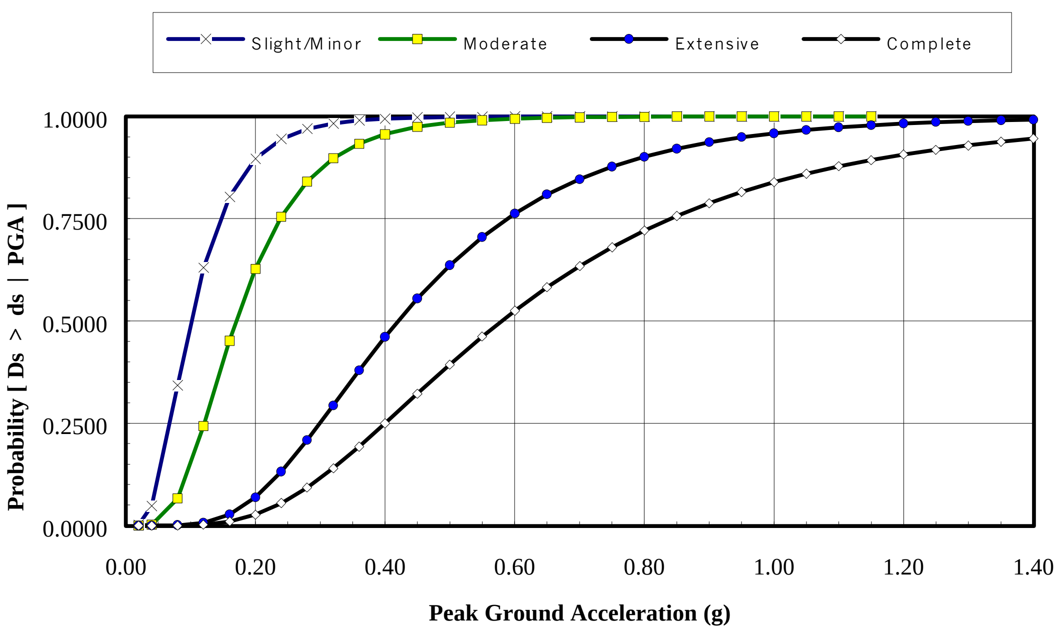


Figure 8.55: Fragility Curves for Small Generation Facilities with Unanchored Components.

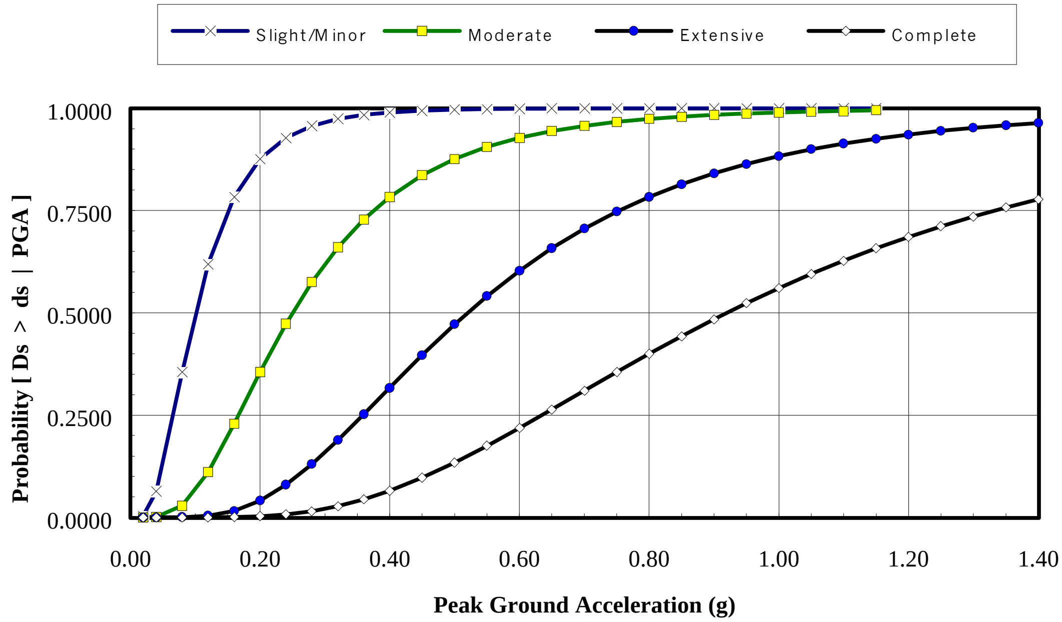


Figure 8.56: Fragility Curves for Medium/Large Generation Facilities with Anchored Components.

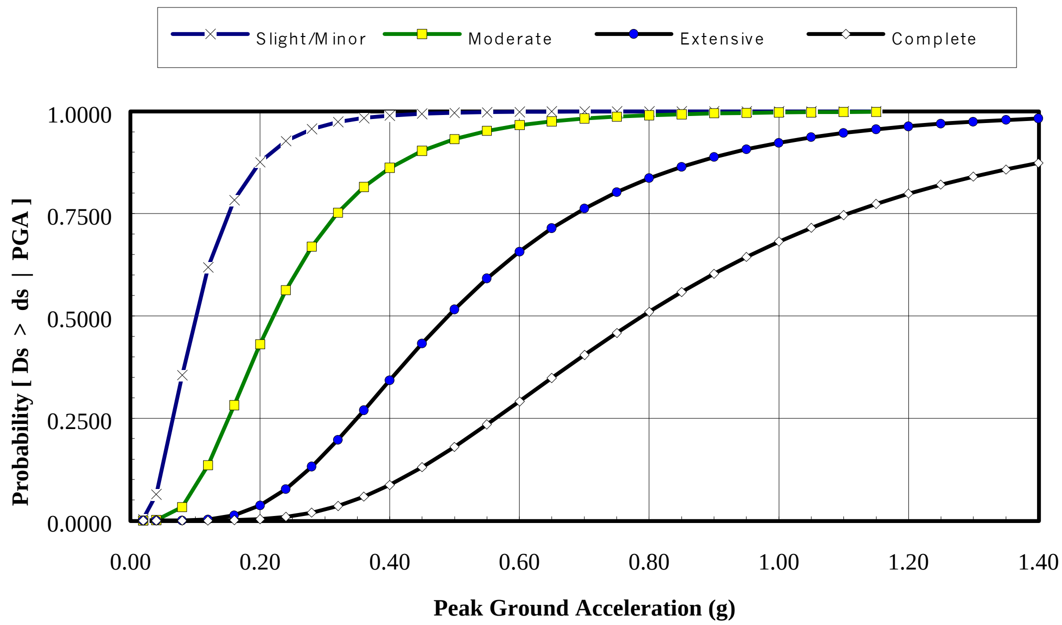


Figure 8.57: Fragility Curves for Medium/Large Generation Facilities with Unanchored Components.

8.6 Communication Systems

8.6.1 Introduction

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

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

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

8.6.2 Scope

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

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

8.6.3 Input Requirements and Output Information

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

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

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

8.6.4 Form of Damage Functions

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

8.6.5 Description of Communication System Components

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

8.6.6 Definitions of Damage States

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

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

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

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

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

<u>Extensive Damage</u> (ds_4)

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

<u>Complete Damage</u> (ds_5)

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

8.6.7 Component Restoration Curves

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

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

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

Table 8.30.b: Discretized Restoration Functions for Communication Facilities

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

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

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

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

8.6.8 Development of Damage Functions

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

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

Table 8.32: Damage Algorithms for Communication Facilities

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

8.6.9 Guidance for Loss Estimation Using Advanced Data and Models Analysis

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

8.6.10 References

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

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

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

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

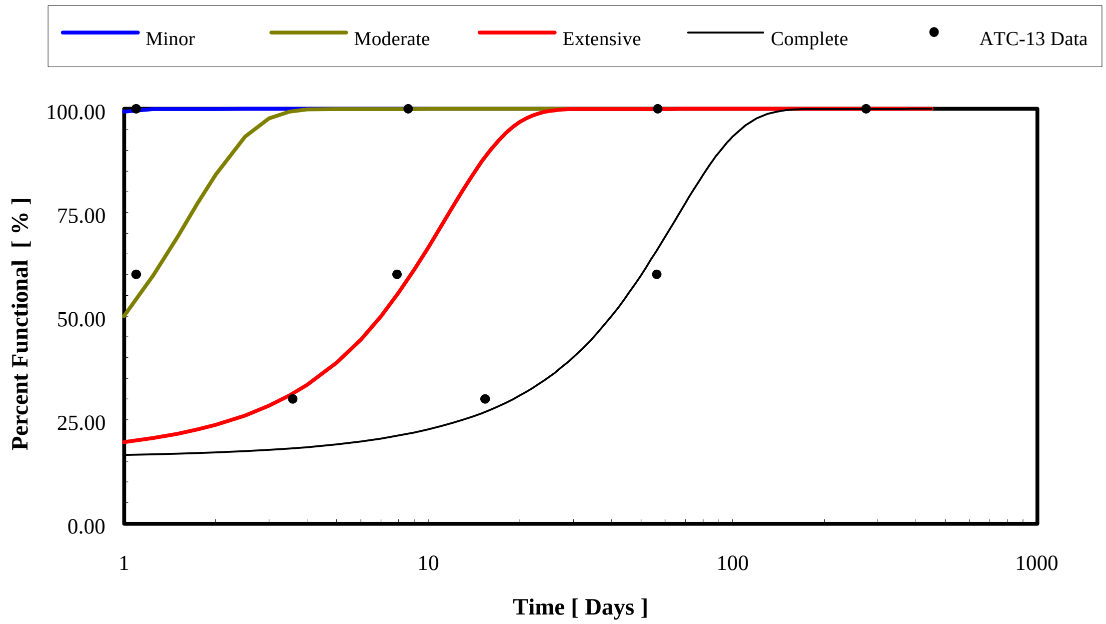


Figure 8.58: Restoration Curves for Central Offices (after ATC-13, 1985).

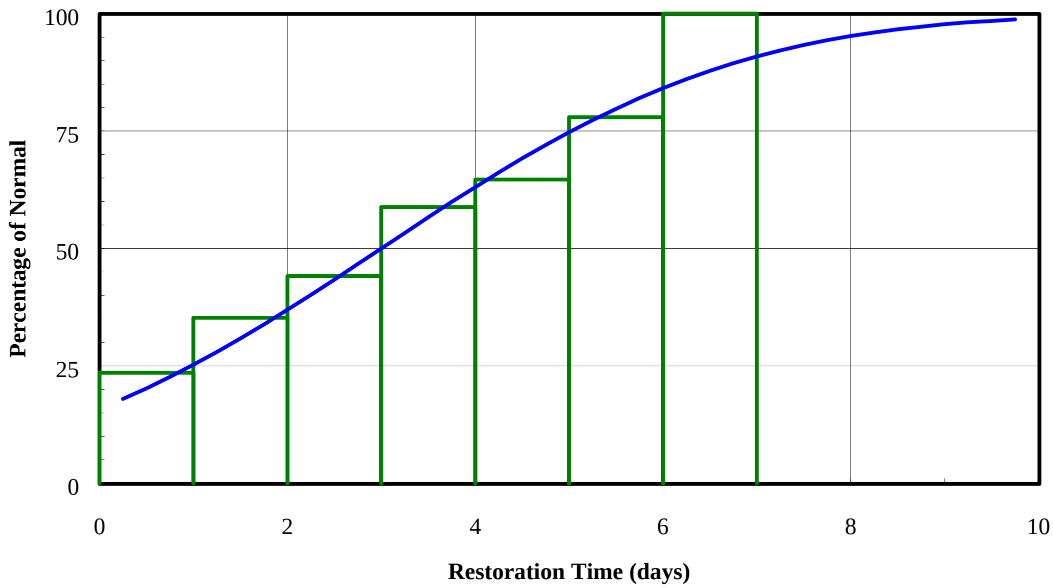


Figure 8.59: Restoration Curve for Communication System Service: Normal Service (After G&E, 1994).

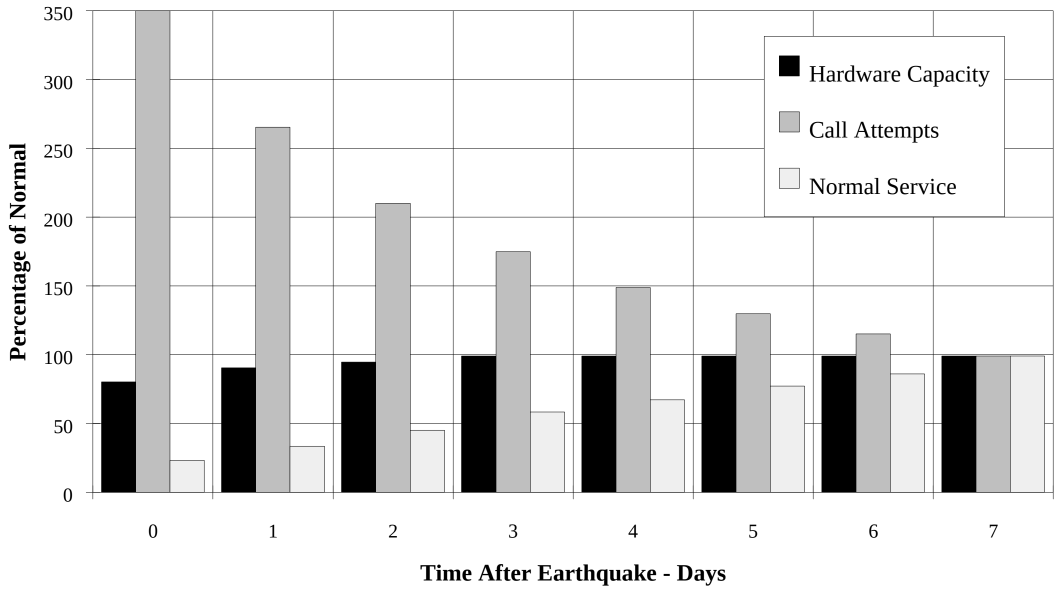


Figure 8.60: Communication System Service Restoration (after G&E, 1994).

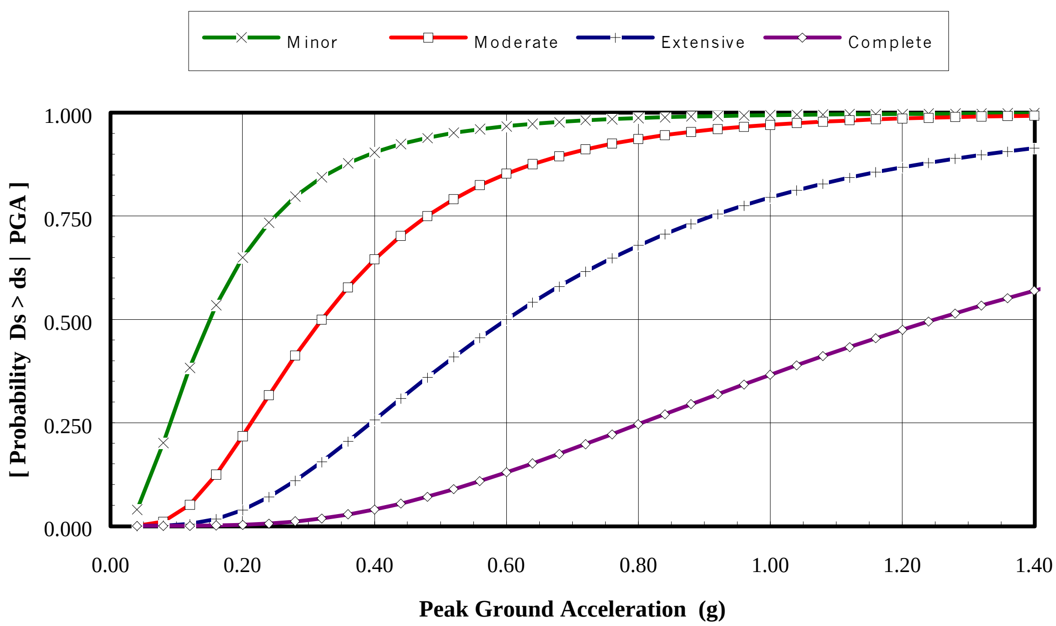


Figure 8.61.a: Fragility Curves for Communication Systems with Anchored Components.

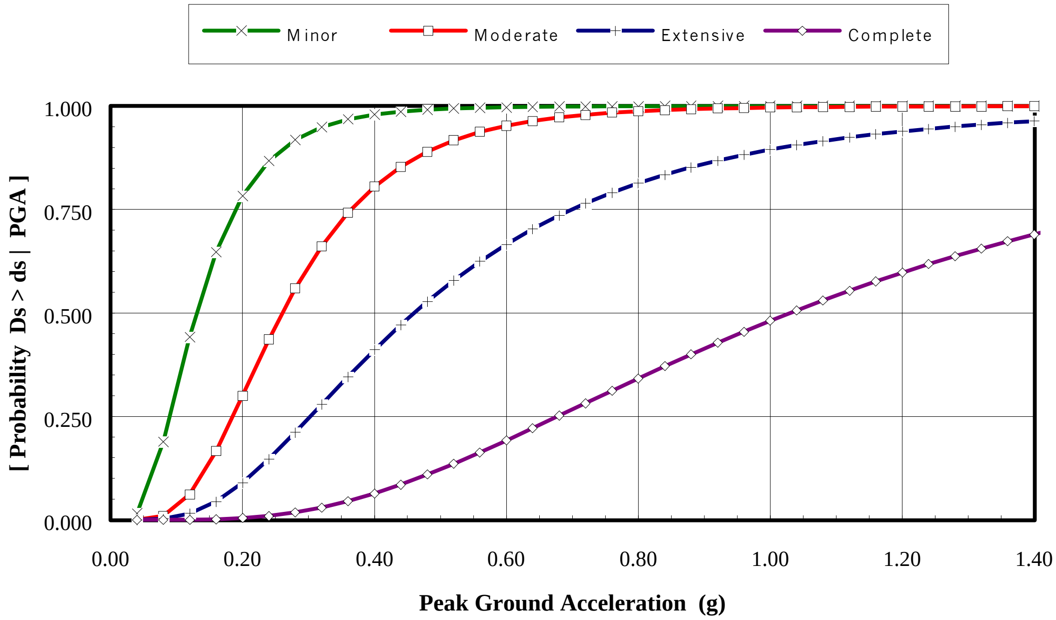


Figure 8.61.b: Fragility Curves for Communication Systems with Unanchored Components.

Appendix 8A
Subcomponent Damage Functions for Potable Water Systems

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

APPENDIX 8B
Subcomponent Damage Functions for Waste Water Systems

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

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

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

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

APPENDIX 8C
Subcomponent Damage Functions for Oil Systems

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

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

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

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

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

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

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

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

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

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

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

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

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

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

APPENDIX 8D
Subcomponent Damage Functions for Electric Power Systems

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

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

* Damage state depends on the percentage of the subcomponents failing

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

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

* Damage state depends on the percentage of the subcomponents failing

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

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

* Damage state depends on the percentage of the subcomponents failing

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

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

* Damage state depends on the percentage of the subcomponents failing

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

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

* Damage state depends on the percentage of the subcomponents failing

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

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

* Damage state depends on the percentage of the subcomponents failing

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

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

* Damage state depends on the percentage of the subcomponents failing

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

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

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

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

APPENDIX 8E
Subcomponent Damage Functions for Communication Systems

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

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

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

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

Chapter 9
Induced Damage Models - Inundation

9.1 Introduction

Flood-induced damage in an earthquake can result from tsunamis (seismic sea waves), seiches (sloshing effects in lakes and bays) or dam or levee failure. Especially in the case of dams and levees, a single structure's failure could result in large losses, which implies that a site-specific analysis should be done rather than using the methodology, which is designed to estimate losses based on probabilities of performance across large inventories. Therefore, the potential exposure to earthquake-caused inundation is computed in the methodology, while prediction of losses or the likelihood of losses is excluded. Figure 9.1 illustrates the relationship of the inundation module to other modules in the methodology.

9.1.1 Scope

The purpose of this module provides the methods for assessing inundation loss potential due to dam and levee failure, tsunami and seiche. For each of these hazards, various levels of results can be obtained according to the complexity of the evaluation, data requirements, and the use of expert assistance to perform the assessment.

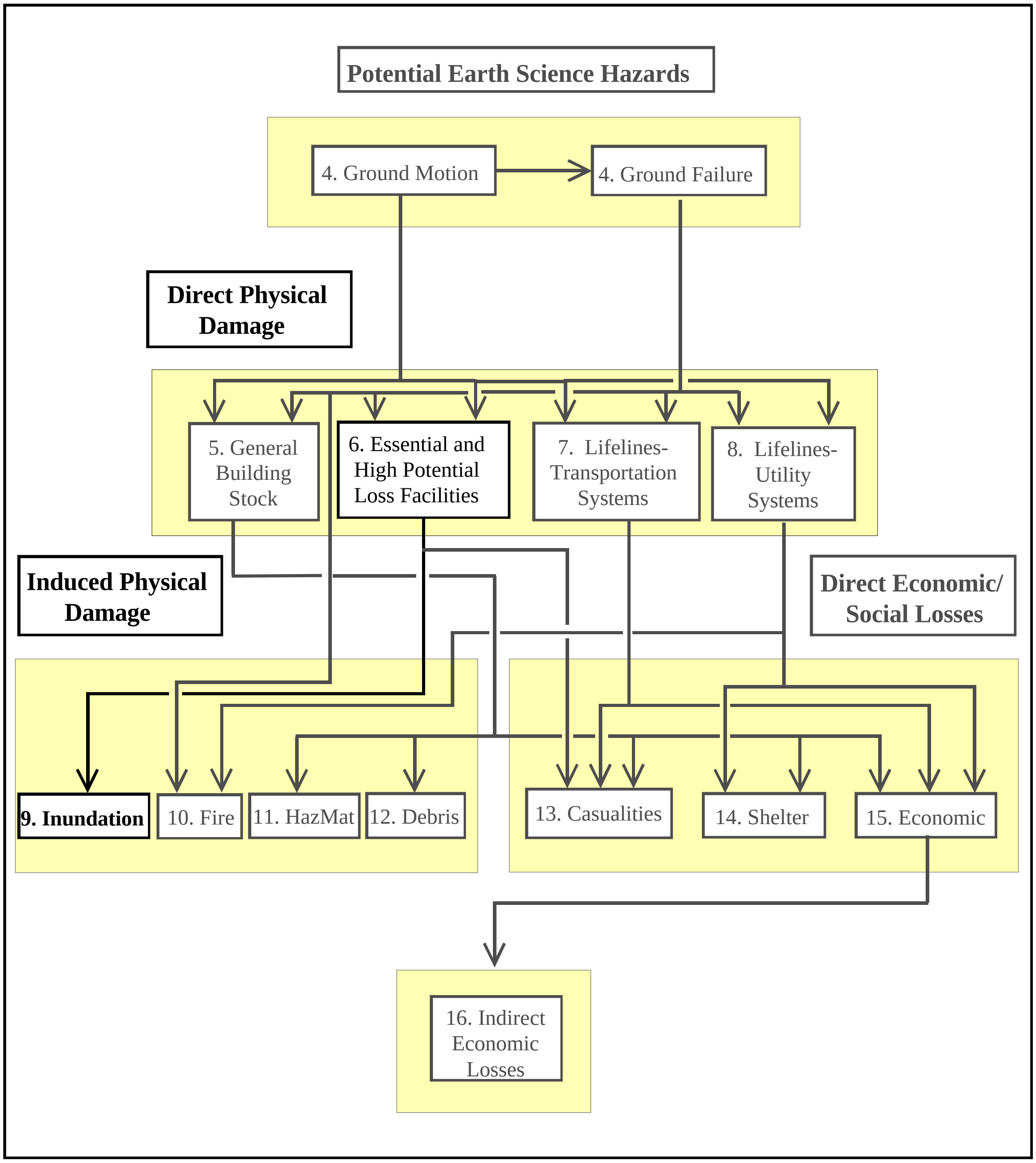
The purpose of this module is to identify the potential sources of flooding in a study area and overlays existing inundation maps with other data to identify the potential exposure. If existing inundation maps are not available, creating inundation maps will require the involvement of experts to perform sophisticated evaluations.

9.1.2 Form of Inundation Estimate

In using existing inundation maps care must be taken in interpreting the results. These maps usually are based on worst-case assumptions, such as a dam being completely full and failing catastrophically, and rarely is such a scenario tied to a specific earthquake scenario.

In general, a complete characterization of flood hazard includes an assessment of:

- Area of inundation
- Depth and velocity of flooding
- Arrival time of the flood following the occurrence of the earthquake, such as in the case of a dam or levee failure or tsunami
- Probability of the above described event



Flowchart 9.1: Relationship of inundation Module to other Modules in the Earthquake Loss Estimation Methodology

The information on inundation that is reported will vary from analysis to analysis. Only in a detailed engineering analysis, as described above, is a complete characterization of the inundation provided.

For each source of flooding (dam or levee failure, tsunami and seiche), the primary format for the presentation of the hazard will be an inundation map. An inundation map identifies the bounds of the area that will be inundated. The bounds can be used to evaluate the population and economic values in the affected area. When digitized for entry into a GIS system, the area of inundation could be overlaid with a topographic map to infer the depth of flooding. However, in the current methodology, this capability does not exist. Figure 9.1 provides an example of an inundation map.

9.1.3 Input Requirements and Output Information

This subsection defines the input requirements and output information for the induced damage inundation module. Subsection 9.1.3.1 describes the input requirements, followed by subsection 9.1.3.2 providing the output information.

9.1.3.1 Input Requirements

9.1.3.1.1 Dam Failure

The input information comes from a default database developed from the National Inventory of Dams database (NATDAM) [FEMA, 1993]. The database identifies all dams in the United States that satisfy the minimum size or hazard criteria given in Table 9.1. For each dam, the database contains multiple fields of information related to the dam and the body of water impounded by the dam. Hazard classifications are found in Section 9.1.3.2.1. Where they exist, inundation maps can be collected. The availability of inundation maps can be determined by contacting the following organizations:

- State or federal dam safety or water resources regulatory agencies
- State office of emergency services
- Local emergency services, law enforcement, or fire protection agencies
- Dam owner (which may be a private individual or organization or public agency such as the U.S. Army Corps of Engineers or Bureau of Reclamation).

Table 9.1 National Inventory of Dam - Size and Hazard Criteria

Category	Criterion	Excluded
Dam Height	Structural Height (H) ≥ 25 ft.	C ≤ 15 acre-feet maximum capacity regardless of dam height
Reservoir Size	Reservoir Impoundment Capacity (C) ≥ 50 acre-feet	H ≤ 6 feet regardless of reservoir capacity
Hazard	Any dam that poses a "significant" threat to human life or property in the event of its failure.	

9.1.3.1.2 Levee Failure

Unlike dams, a national inventory for levees does not exist. The user must contact local sources to identify levees in the study region. Possible sources include United States Army Corps of Engineers district offices, local flood, reclamation, or levee maintenance control districts, the United States Soil Conservation Service, and municipal or county authorities. The user must provide the geographical location of the levees (represented in the methodology software as polylines). Additional information that should be included in the levee inventory includes the levee design basis (e.g., 100 year flood), the levee crest elevations, normal water level elevation, and levee owner/operator.

Since most levees and in some locations floodwalls are designed to provide protection during periods of flooding, they are typically dry (i.e., do not impound/retain water) at the majority of the time. As a result, seismic failure of a levee during non-flood conditions does not pose an inundation hazard. As part of the process of identifying levees in the study region, the user should also obtain information as to whether the levee is dry the majority of the year (e.g. greater than 75% of the time). If this is the case, the levee might be screened out from further consideration, unless a study of the worst-case scenario is desired

Existing levee inundation maps are used to identify areas that may be flooded in the case of a failure. It is unlikely that an existing levee inundation study will be available. If a study is available, it should be reviewed to determine whether the water level used is consistent with the level that can be expected when an earthquake occurs.

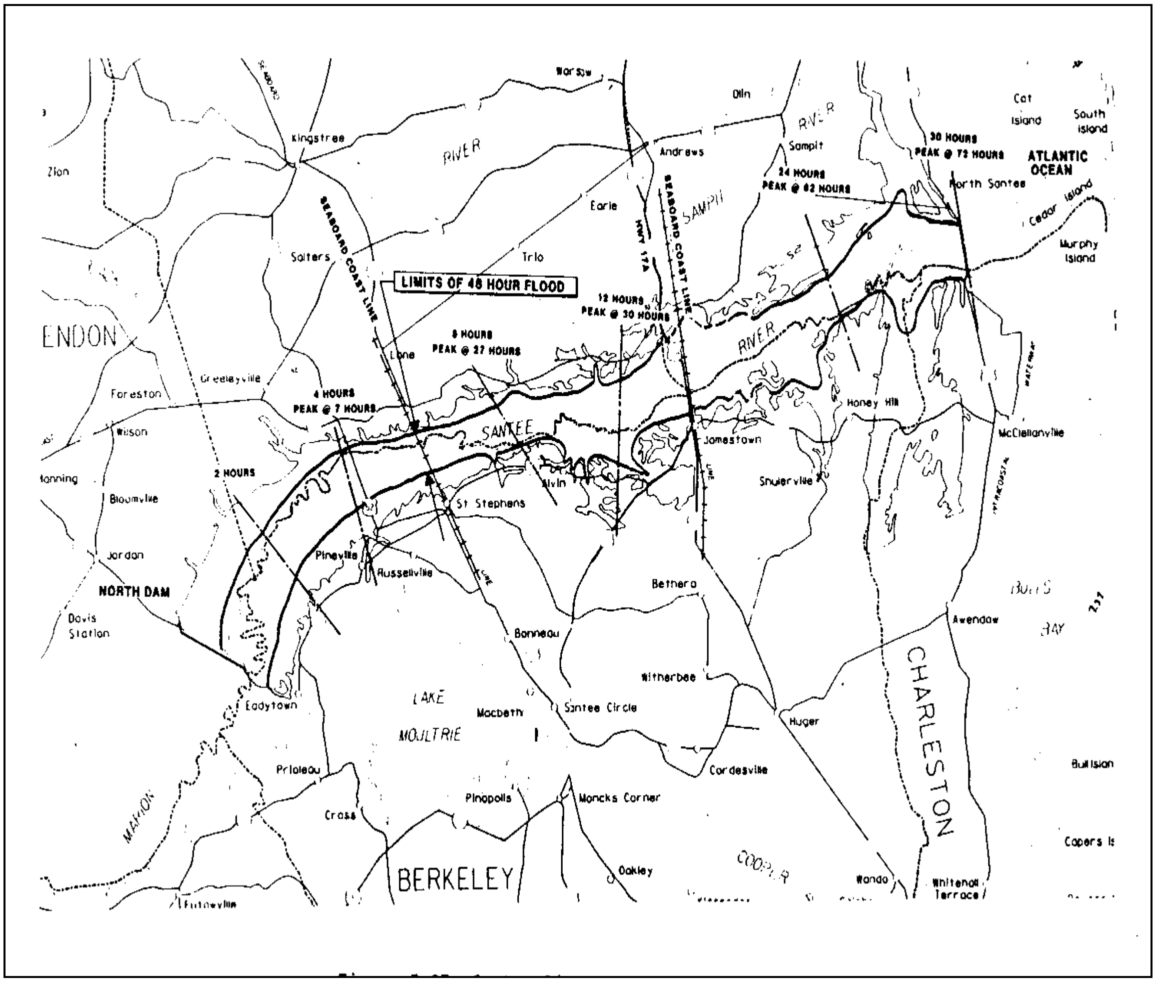


Figure 9.1 Dam failure inundation map.

9.1.3.1.3 Input Requirements - Tsunami

The first objective in the analysis of tsunami is to simply identify whether a tsunami hazard exists. To accomplish this, the following information is needed.

- Location of the earthquake (on-shore or off-shore event)
- Type of faulting

If the earthquake source is on-shore there is no tsunami hazard. The same is true if an offshore event occurs that involves primarily strike-slip movement. Alternatively, if the earthquake occurs offshore and significant vertical displacement of the seafloor occurs and a tsunami exists. The assessment of tsunami inundation in the methodology is for nearby seismic events only. Tsunami inundation maps based on distant events should not be combined with the study region scenarios. For example, a tsunami affecting the West Coast generated by and earthquake in Alaska should not be combined with the study of losses occurring from an earthquake in Los Angeles.

The user should determine the size and location of the earthquake that was assumed to estimate the tsunami inundation or, if specified, the mean return period of the tsunami. This will provide a basis to judge whether the existing inundation map conservatively or un-conservatively estimates the inundation that would be produced by the study earthquake. In cases where a scenario earthquake would generate a tsunami, the probability basis of the tsunami inundation map should match that of the scenario earthquake. For example, if an existing tsunami inundation map based on wave run-ups caused by local earthquake that have a mean return period of 500 years for a study region in Alaska, then the scenario earthquake selected for use with the methodology should also have a 500 year return period. Otherwise, the tsunami and the earthquake loss outputs should not be combined because this would describe different events.

9.1.3.1.4 Input Requirements - Seiche

To first step in seiche analysis is to identify natural or man-made bodies of water where a seiche may be generated. The default database of dams can be used to identify the man-made bodies of water (see Section 9.1.3.1.1) while the user must generate an inventory of natural water bodies in the study region. The following criteria can be used to identify bodies of water that should be considered in the assessment:

- The lake volume must be greater than 500,000 acre-feet
- There must be an existing population and/or property located in proximity to the lake shore that could be inundated

If these criteria are not met, lakes should not be considered for assessment. Existing seiche inundation maps are used to identify areas subject to flooding. Sources of existing seiche inundation studies include state and federal agencies that regulate dams, dam or lake owners, and state office of emergency services. The availability of such studies is very limited.

9.1.3.2 Output Information

The output of the dam failure inundation module consists of an inventory of the dams located in the study region divided into three groups corresponding to the hazard classifications provided in the database. The hazard classification system is shown in the Table 9.2 below.

Table 9.2 Dam Hazard Classifications

Hazard	Urban Development	Economic Loss
Low	No permanent structures for human habitation	Minimal (undeveloped to occasional structures or agriculture)
Significant	Urban development and no more than a small number of inhabitable structures	Appreciable (notable agriculture, industry)
High	Urban development with more than a small number of inhabitable structures	Serious (extensive community, industry or agriculture)

In addition to the inventory of dams located in the study region, the analysis will utilize existing digital dam inundation maps to identify the population and property at risk due to the dam failure.

The output of levees analysis is an inventory of the levees in the study region whose failure could lead to flooding. In addition to the inventory of levees located in the study region, analysis can use existing digital levee, tsunami, and seiche inundation maps (limited availability) to quantify the population and property at risk due to the failure of levees.

9.2 Description of Methodology

9.2.1 Dam Failure

This subsection describes the approach used to perform analyses for inundation due to dam failure. To start the analysis of dams, the dams that are located in the study region have to be identified. To do this, a geographic search through the default dam database is conducted. Based on the dam hazard classification, a list of the Low, Significant and High Hazard dams can generated. Note that "hazard" here means the danger posed if the dam fails, and is not a description of the probability of such failure. Next, an analysis using existing digital inundation maps is conducted to estimate the potential population and economic value impacted by a dam failure.

9.2.2 Levee Failure

The tasks and analysis tools are similar to those required for dam failure. An inventory of levees located in the study region is generated by contacting local, state and federal agencies. The inventory should typically include levees that act as water barriers greater than 10 percent of the time. This excludes from the inventory levees that remain dry except during short periods of flooding, because of the small probability the earthquake will coincide with a time of high water level. Existing levee failure inundation studies are used to identify areas that may be impacted by levee failure. When using existing inundation studies, the following should be considered:

- Existing inundation studies must be reviewed to determine assumptions regarding water levels
- The analyst should identify areas where levee failure will have the most severe impact; existing studies may not have used this approach

9.2.3 Tsunami

This subsection describes the approach to perform evaluations for inundation due to tsunami. Existing tsunami studies may include inundation maps for the scenario earthquake. However, they should be reviewed to verify the assumptions on which the tsunami was based. As explained above, tsunami inundation maps developed for distant earthquakes should not be used in combination with a local scenario event. However, the methodology can be used to independently estimate the population and building value at risk from a distant event tsunami simply by using a representative inundation map in which case these results would not be combined with those of a local earthquake scenario.

9.2.4 Seiche

This subsection describes the approach to perform evaluations for inundation due to seiche. Existing seiche inundation studies are used to identify the areas where flooding may occur. However, in most cases such studies do not exist. In some cases the results of a seiche analysis may be available that did not produce an inundation map. In this case, the user could transfer the results to a topographic map of the lakeshore area to determine the bounds of inundation.

9.3 Guidance for Expert-Generated Estimates

Losses that might be caused by earthquake-caused flooding are not calculated within the methodology, because of the facility-specific evaluation by experts that is necessary. The information in this section is not intended to supplant the need for experts when a loss study is extended into these induced hazards, but rather to provide these civil engineering, hydrological, and geotechnical experts guidance to standardize their analyses.

9.3.1 Dam Failure

The greatest uncertainty lies in the likely cause, mode, degree and time sequence of failure. Another uncertainty involves flood routing and limits of inundation downstream of the failed dams. Although several historical dam failures have been documented, very few have provided an exact description of the hydraulics of the failure flood.

The hydraulic characteristics of a surge released from a dam failure depends on the size, shape and position of the breach, volume of water stored behind the dam, the dam height, width and length of the reservoir, and the reservoir inflow and tailwater condition at the time of the failure. To provide uniformity in the evaluation of the effects of dam failure during a seismic event, the following guidelines are provided. These guidelines should be followed unless deviations are appropriate in the opinion of an expert analyst.

Antecedent Conditions - Reservoir levels generally predictably related to the purpose of the reservoir. Whereas a seismic event can occur anytime during the year, the following guidance is provided:

1. Reservoir Conditions - It should be assumed that the reservoir is at the average operational level for the season when water levels are highest. If the average operational level is not known, the maximum normal depth of water should be used.
2. Antecedent Flow - Unless a dam has failed due to failure of an upstream dam, the antecedent stream flow into the reservoir is assumed equivalent to the mean monthly flow for the season assumed for the scenario. If the failure is assumed to occur during the flood season, then the mean annual flood for the month is assumed. This antecedent flow can also be applied as the base flow downstream of the dam.

Tailwater Condition - No assumption on the varying tailwater condition is necessary when using DAMBRK, a program developed by the National Weather Service (NWS), because the model automatically calculates the tailwater elevation based on the base flow and outflow from the spillway or breach formation. The model does appropriate correction for submergence automatically.

River Cross-Section - For the purpose of representing the river channel in the DAMBRK model (see Figure 9.2), cross-sections of the river at selected critical stations are normally taken from U.S.G.S. 7 1/2 minute topographic maps. Since only 8 elevation-top-widths data points can be accepted by DAMBRK, care should be used in selecting cross-section data for the stations along the river or valleys to assure accurate estimates of flood elevations.

Mode of Failure - A conservative estimate of flooding due to a dam failure would assume complete disappearance of the dam. For small concrete dams, such an assumption may be reasonable. However, for large concrete gravity dams, it is more reasonable to assume partial breach with some parts of the dam remaining intact. For example, embankment dams will generally fail by erosion.

Shape and Size of Failure - Breach shapes are assumed to follow regular geometrical shapes such as a triangle, rectangle, trapezoid, or parabolic figure. Failure depth is always assumed equal to the total height of the dam unless there is a high tailwater. Table 9.3 gives guidance on the various parameters that could be assumed for a given breach shape and size.

Time to Maximum Failure - This is one of the most unpredictable parameters in dam break modeling. To facilitate the adoption of reasonable values of time to maximum failure, Table 9.3 gives recommended values for various types of dams.

Expansion and Contraction Coefficients - The manual for DAMBRK recommends values of cross-section contraction/expansion coefficients for the contraction or expansion of the downstream reach's cross-sectional geometry. Contraction values generally vary from 0.1 to 0.3 while expansion values usually vary from -1.0 to -0.1. If contraction-expansion effects are negligible, a value of 0.1 is used.

Table 9.3 Suggested Breach Characteristics (see Figure 9.3)
(Fread, 1982)

Parameter	Value	Type of Dam
Average Breach Width (BR)	W = Crest Length	Arch
	H = Dam Height BR = Width of 1 or more monoliths, usually BR ≤ 0.50W	Masonry, Gravity
	HD < BR ≤ 5HD (usually between 2HD and 4HD)	Earthen, Rockfill, Timber Crib
	BR > 0.8 Crest Length	Slag, Refuse
Horizontal Component of the Side Slope of Breach (Z)	0<Z≤ Slope of the Valley Walls	Arch
	Z = 0	Masonry, Gravity, Timber Crib
	1/4 < Z ≤ 1	Earthen (engineered compacted)
	1 < Z ≤ 2	Slag, Refuse (non-engineered)
Time to Failure (TFH) (hours)	TFH < 0.10	Arch
	0.1 < TFH ≤ 0.3	Masonry, Gravity
	0.1 < TFH ≤ 1.0	Earthen (engineered compacted), Timber Crib
	0.1 < TFH ≤ 0.5	Earthen (non-engineered, poor construction)
	0.1 < TFH ≤ 0.3	Slag, Refuse

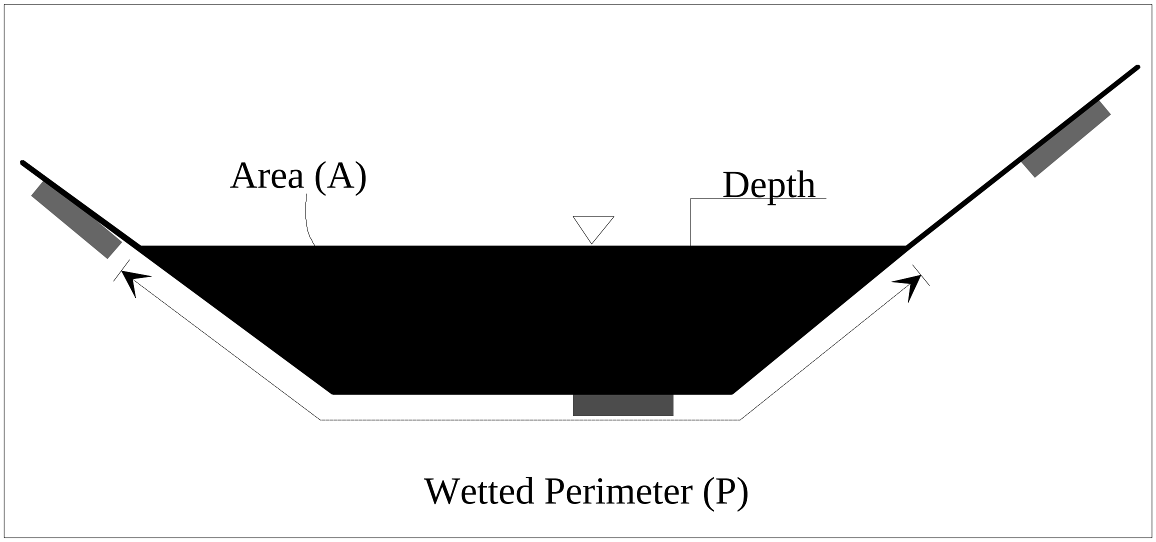


Figure 9.2 Illustration of a channel cross-section.

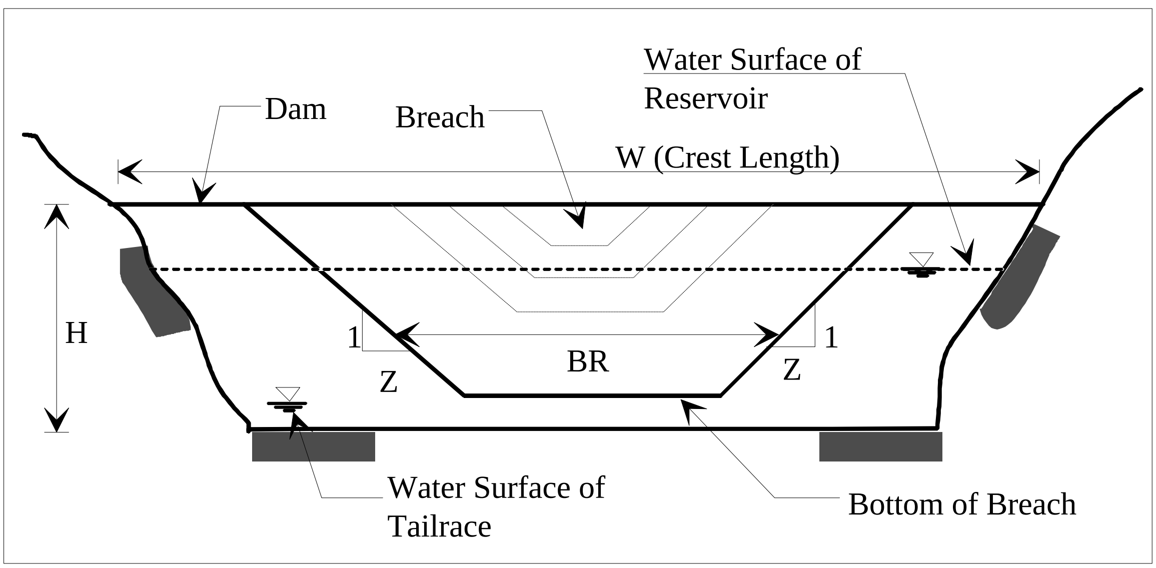


Figure 9.3 Definition sketch of the breach parameters.

Roughness Coefficients - Manning's "n" which represents the roughness of the river channel is the most indeterminate variable in dam break modeling. Calibrated values from high-water marks cannot really be used to represent those expected under a dam failure flood. Published data such as those from the U.S.G.S. can only be used to approximate the expected value from the hypothetical flooding. Therefore, it is necessary that relatively reasonable values be assumed or considered before a flood plain analysis is started. In most cases, these assumed values are varied through the modeling effort in order to resolve non-convergence problems with DAMBRK.

Table 9.4 Recommended Values of Manning's n
(US Dept. of Transportation, 1980)

Channel Type	n Values
1. Fairly regular section	
a. Some grass and weeds, little or no brush	0.30-0.035
b. Dense growth of weeds, depth of flow materially greater than weed height	0.35-0.05
c. Some weeds, light brush on banks	0.35-0.05
d. Some weeds, heavy brush on banks	0.05-0.07
e. Some weeds, dense willows on banks	0.06-0.08
f. For trees within channel, with branches submerged at high stage, increase all above values by	0.01-0.02
2. Irregular sections, with pools, slight channel meander; <u>increase</u> values given above about	0.01-0.02
3. Mountain streams, no vegetation in channel, banks usually steep, trees and brush along banks submerged at high stage:	
a. Bottom of gravel, cobbles, and few boulders	0.04-0.05
b. Bottom of cobbles, with large boulders	0.05-0.07

Routing - Generally the flood wave from a hypothetical dam break flood should be routed downstream to the point where the failure will no longer constitute a threat to human life or property. The results of the routing should be plotted on inundation maps with the dam break flood wave travel time and flood depths indicated at critical downstream locations.

9.3.2 Levee Failure

The guidance for expert generated inundation due to levee failure is essentially the same as the guidance for dam failures. The NWS DAMBRK software is used to determine the flooding due to levee failure. However, in the case of levee failure the analyst should consider multiple locations for levee failure based on a consideration of the locations where the levee may be most vulnerable and where the impact of flooding in the study area would be greatest.

9.3.3 Tsunami

The most detailed work on inundation map preparation from tsunami has been conducted for Hawaii, though sophisticated analyses have also been conducted for areas of the West Coast. Therefore, most guidelines refer to the work in this state. However, it should be noted that even though the following guidelines have been applied to Hawaii, the same procedures and assumptions could be adapted to other coastlines of the country that would be subject to tsunami flooding.

Tsunami inundation maps that have been produced are based on computer programs that are considered state-of-the-art. However, these programs are still short of the accuracy attainable by hurricane and storm-surge simulation programs. A two-dimensional model is recommended for modeling of tsunami for inundation studies. The available two-dimensional models solve the non-linear shallow water long wave equation using different methods of finite difference solution. A complete description of the available and verified models in the United Sates is provided in Bernard and Gonzalez, 1994. Numeric models are used to make scenario specific tsunami assessments. Inputs required for this assessment include detailed information on the location of earthquake and fault movement that is expected to occur on the ocean floor. In addition, information is needed regarding the bathymetry of the ocean floor, shoreline geometry, topographic data and tide information. Good quality bathymetric and topographic data are essential for accurate inundation model results.

9.3.4 Seiche

A detailed assessment is performed to estimate the seiche hazard at natural and man-made bodies of water. Input to this assessment includes the length, width and depth of each body of water and rim topographic and geologic information required to assess landslide potential and wave run-up. The length and width of the lake or reservoir correspond to the average dimensions of the body of water where wave generation is evaluated. The user may have to consider a number of different wave geometries to determine the critical dimensions that generate the largest estimated wave height. At a minimum, geologic maps of the lake or reservoir rim or landslide potential maps should be obtained. In addition, for earthquakes that occur on faults along or within bodies of water, the location of the event and the magnitude of vertical fault displacement is required.

A simple calculation is performed to determine the maximum wave height that would be generated by an earthquake. The following relationship can be used to estimate the peak wave height.

$$H = \sqrt{\frac{A}{L(p\,f)^2}} \tag{9-1}$$

where:

H = peak wave height (cm)
A = peak ground acceleration (in g's)
f = frequency of the lake (Hz)
L = Wavelength = 5.12 / f^2

The above approach is a simplified method to estimate the peak wave height of a seiche generated by seismic motion at the lake. As part of this assessment the analyst must consider the occurrence of waves along alternative axes in the lake. Since the natural period of the lake is based on its shape, the period will be different on different axes.

Oscillations of water bodies above and below their mean level have a natural period depending upon the physical features of the water body. A disturbing force with the same period of oscillation as the lake or pool builds up the seiche to the point where the energy dissipated by friction equals the rate of application of energy. When the force causing the displacement ceases or changes in intensity, a series of pulsations follow at the natural frequency until damped by frictional forces. Standing waves of large amplitude are likely to be generated when the causative forces which sets the water basin in motion is periodic in character, especially if the period of these forces is the same as, or is in resonance with, the natural or free oscillation period of the basin.

The period of the seiche is dependent on the geometry of the basin. This period can be estimated with Merian's equation.

$$T_n = \frac{2l_b}{n\sqrt{gd}} \tag{9-2}$$

where:

T_n = period in seconds
l_b = length of the basin
n = number of nodes 1,2,3,...
g = gravitational acceleration
d = depth of water

For the fundamental and maximum period (T_n for n=1),

$$T_1 = \frac{2l_b}{\sqrt{gd}} \tag{9-3}$$

However, the preceding equation is based on the assumption of uniform and constant cross-section in the basin. In a basin of irregular section, the period is given by integrating equation 9-4. The frequency of the basin is the reciprocal of the period.

$$T = 2\int_0^{l_b} \frac{dx}{\sqrt{gd}} \tag{9-4}$$

where dx = finite increment of l_b.

9.4 Inundation References

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