



Open-Source Risk Estimation Software

Prepared for
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ABSTRACT

Risk analysis is a critical link in the reduction of death and destruction due to earthquakes. Recognition of this has led to a rapid rise in demand for accurate, reliable and credible risk analyses. A bottleneck exists however between the wealth of high quality scientific data generated by researchers, and the demands of end-users – that bottleneck is the dearth of readily available, user-friendly transparent risk analysis software to meet the wide variety of end-user needs. This situation, of strong demand for user-adaptable software, has emerged in many fields and has been met by the Open Source movement with solutions such as *Linux*, *OpenOffice*, *Mozilla* and *Wikipedia*. This trend is also strong the seismic arena, as evidenced by the emergence of *OpenSHA* and *OpenSEES* serving critical parts of the field. Open-source risk (OSR) software meets this demand and also advances research and enhances training in a variety of catastrophe-related disciplines.

This report documents the initial design of *OpenRisk*, an OSR application for quantifying risk to individual facilities and portfolios of facilities in terms of probabilistic repair costs, human casualties, and loss of use (“dollars, deaths, and downtime”). *OpenRisk’s* initial development will focus on seismic risk to individual facilities via traditional loss-estimation algorithms, with subsequent developments addressing portfolio risk, performance-based earthquake engineering analysis of single facilities, and eventually risk from wind and other hazards. This report is organized to first provide a development roadmap for *OpenRisk*, including a brief overview of the fields of loss estimation and performance-based earthquake engineering (PBEE), a brief review of existing loss-estimation and PBEE software, a mission statement for *OpenRisk* and a proposed development approach. A significant part of the report then documents risk algorithms as a major first step towards programming. Next, an initial list and summary specification of software objects employing these algorithms is provided, together with draft development guidelines. Finally, initial data structures are documented, along with a seed database of structure types, seismic vulnerability functions, and damage probability matrices, followed by Appendices providing supporting information. As *OpenRisk* is anticipated to develop dynamically, so is this report, with releases and feedback requests available online at www.risk-agera.org.

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1 INTRODUCTION

1.1 THE AGORA FRAMEWORK

This document begins the design of open-source software for the estimation of multihazard risk. Since successful open-source software must be dynamic, so is its design, and so is this report. The initial release of this report is intended to be developed further but provides enough detail to allow programmers to begin coding useful OpenRisk components. (Coding began in summer 2006 at the US Geological Survey's Golden CO office, using an incomplete draft that was also provided to the USGS's Pasadena CA office.) The initial release of this report is made through the Southern California Earthquake Consortium (SCEC), thanks to its seed funding. Future revisions of this report will be disseminated by the Alliance for Global Open Risk Analysis (AGORA, www.risk-agera.org).

Box 1. The AGORA framework

Whereas, risk analysis is the foundation of risk reduction, and

Whereas, we all share natural and technological hazards risk, and

Whereas, risk analysis is most broadly accepted and used when

- Risk methodologies are open
- Risk software is open source, and
- Fundamental risk data (such as hazard and vulnerability) are open,

Therefore, we support

- Open risk analysis
- Open risk methodologies
- Open risk tools, including open-source software
- Open risk data (such as hazard and vulnerability)
- Shared and collaborative development of methods, tools and data, and
- Open communication of risk results

While respecting individual initiative and the individual's right to the fruits of that initiative.

1.2 OVERVIEW

Traditional loss-estimation (LE) software has existed since the 1970s to assess multi-hazard risk to large numbers of buildings, based on observations of environmental excitation (e.g., shaking intensity) and loss (financial and otherwise), for statistically significant numbers of buildings and other facilities such as bridges, equipment, etc. One can think of this approach as category-based loss estimation, since it describes the performance of categories of facilities (e.g., woodframe dwellings) as opposed to particular, individual buildings. A second-generation performance-based earthquake engineering methodology (PBEE-2) has developed since the mid-1990s with the potential to assess risk to individual buildings in terms of dollars, deaths, and downtime, given seismic hazard, with a greater degree of scientific defensibility and deeper insight into seismic vulnerability. (The earliest research dates back at least to the 1970s, but only since around 2000 has PBEE matured to the point where researchers and practitioners reasonably expect to implement it.) Recent work by SCEC researchers enhances the treatment of hazard, for example using physics-based modeling.

In collaboration with Ned Field of the USGS and SCEC programmers, this report presents a loss-estimation methodology that combines SCEC's OpenSHA with traditional category-based loss estimation and eventually PBEE-2. The methodology will ultimately be implemented in open-source computer code and are both referred to here as *OpenRisk*. OpenRisk will integrate data on seismic hazard, vulnerability, values exposed to loss, and societal consequences to enable individual researchers to explore system-level implications of their research without needing universal mastery. The development of open-source software follows an emerging trend for openness and transparency exemplified by Linux, OpenOffice, Wikipedia, OpenSHA, and OpenSees (a structural-analysis product of PEER). This trend (open-source software) is characterized by an open flat dispersed multi-agent development process, as opposed to traditional closed centralized hierarchical software development.

The development process begins with a development roadmap containing introduction, background (a brief history of loss-estimation software), mission statement, design

principles, procedures to validate results against data, code-review and QA procedures, development timeline, project management, and document history.

The algorithm for calculating risk using OpenSHA and category-based loss estimation is documented, along with the requirements of how OpenRisk will perform those calculations. These materials have been reviewed during the development process by one or more of OpenRisk's drivers, who, other than the PIs, include three Caltech professors, one professional lifeline engineer, a USC professor, and two USGS researchers, all currently contributing their time on a voluntary basis. Preliminary coding was performed in the 2006 SCEC year, in collaboration with Ned Field, SCEC, and USGS programmers.

1.3 ORGANIZATION OF THE REPORT

This document is organized as follows. This chapter has introduced the OpenRisk project. Chapter 2 contains a development roadmap. Risk algorithms for single buildings are presented in Chapter 3, while Chapter 4 presents algorithms for portfolios of buildings. Chapter 5 provides an initial list of software objects to be developed and provides UML-like detail on many of them. Chapter 6 provides various seismic vulnerability functions as seed data. Development guidelines are listed in Chapter 7. Chapter 8 lists references cited.

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2 DEVELOPMENT ROADMAP

This chapter summarizes the intended roadmap for developing OpenRisk. It begins with a brief history and the current limits of loss-estimation software, to provide context for OpenRisk. The OpenRisk mission statement is then presented.

2.1 A BRIEF HISTORY OF LOSS ESTIMATION SOFTWARE

Loss estimation and performance-based earthquake engineering. Two engineering disciplines address quantifying the uncertain future seismic performance of buildings and other facilities: loss estimation (LE), which dates from around 1970, and performance-based earthquake engineering (PBEE), which dates from the late 1990s. LE has typically approached the estimation of seismic risk using empirical datasets of the observed damage to large numbers of buildings subjected to earthquakes, supplemented by expert opinion. It has been principally used to estimate earthquake effects at the level of hundreds of buildings or more. PBEE by contrast employs analytical, predictive models of structural response, laboratory studies of the damageability of individual building components, and construction contracting principles, to relate shaking intensity to loss, largely to model the performance of individual buildings and bridges.

Differences and similarities of LE and PBEE are:

- Both use hazard analysis to estimate uncertain future shaking intensity at sites of interest.
- LE then applies vulnerability functions—generally based on empirical and expert-opinion approaches practical at macroscopic (many-building) scales—which directly relate environmental excitation (shaking intensity, windspeed, etc.) to loss for categories of buildings.
- PBEE, by contrast, employs structural analysis to relate shaking intensity to member forces and deformations. PBEE is largely analytical, uses first principles of structural engineering such as structural analysis, and is currently practical at the scale of individual buildings.

- LE inherently offers validation via past disaster experience, but its ability to distinguish the effects of detailed design differences such as quantities of structural sheathing or the type of building foundation depends largely on the availability and specificity of empirical data and whether or not the data were collected in a representative fashion suitable for statistical analysis (including treatment of uncertainty in sample vs. population). This has rarely been done to a level where it is useful beyond gross categories of buildings and not hampered by non-representative sampling of buildings, reliance on expert opinion, and judgment to extrapolate observations to a population scale.
- PBEE explicitly offer validation via reproducible controlled experiments, incorporated into global structural analyses. It can be tailored to the specifics of a building, including critical facilities, and readily addresses questions such as the efficacy of design or code changes.

Computer software for loss estimation and PBEE. Because of the data- and computation-intensive nature of LE and PBEE, computer software has emerged as an integral and necessary part of disaster risk assessment. Probably the first software developed for earthquake and other risk-assessment purposes were those of the Wiggins Company (Hirschberg et al. 1978) and Algermissen (1978). Steinbrugge in the early 1980s had a proprietary computer program he had developed for use by insurance companies (Steinbrugge, personal communication).

Insurance Modelers. In the late 1980s, three loss-modeling companies emerged (Applied Insurance Research, EQE International, and Risk Management Solutions, referred to here as *the modelers*) to serve the global insurance industry. Each was founded from a different perspective: AIR focused on the needs of the London reinsurance market vis-à-vis US hurricane and earthquake, while EQE focused on primary insurance companies with California earthquake risk and approached the problem from a technical perspective. Following the 1994 Northridge earthquake, EQE created a separate entity for the insurance market, EQECAT. RMS was similarly focused on primary insurance companies with California earthquake risk but approached the problem more from a financial and investment perspective. The three companies have since developed into sizable corporations with global

capabilities, providing proprietary modeling software with very sophisticated capabilities, primarily to the finance, insurance and real estate industries. Because their models are proprietary, we will not go into detail, although it should be noted that a research project at Wharton compared and benchmarked the three models for several case study sites (Grossi and Kunreuther, 2005).

As a generalization, the three models tend to have very sophisticated hazard models, typically using the best available databases and enhancing those with proprietary research and development. An example is Japanese seismicity – the Japanese government has recently (2005, http://www.j-shis.bosai.go.jp/j-shis/index_en.html) released new seismic hazard maps that incorporate time dependency on several faults, so that currently the modelers are working to enhance and extend the time dependent aspects for their models. Regarding vulnerability, the modelers tend to have access to insurance company loss data, which are employed for empirically-based vulnerability functions. Additionally, at least two of the modelers have developed structural analytical models, with one model approaching the PBEE capability discussed above. All three modelers also have developed detailed inventories of exposure in selected localities – in fact, that was one of AIR’s founding strengths. Lastly, all three models tend to have sophisticated treatment of probability and uncertainty, both to increase speed (models may be processing several million policies) as well as to satisfy actuarial requirements. This last aspect we refer to as *actuarial-quality* modeling. All three companies generally have models of varying detail and quality for earthquake or tropical cyclone modeling in the US, Canada, Japan, China, Mexico, parts of Europe and Latin American, New Zealand and Australia. On a selected basis, they have also developed flood, hailstorm, wildland fire, terrorism and other models.

In the last decade all three modeling companies have been acquired: AIR by Insurance Services Offices (ISO), EQECAT by ABS Consulting, and RMS by the Daily Mail and General Trust plc (DMGT, who also acquired the Sanborn Map Company). Other modeling firms include Risk Engineering, which offers earthquake and hurricane portfolio analysis software for the US and Canada, Applied Research Associates (ARA), who offer hurricane portfolio software, and Risk Frontiers, who are associated with Macquarie University (Australia) and offer models for the Australasia region.

EPEDAT. In the early 90s the need for general earthquake loss estimation software for use in the public sector became apparent. Two seismic risk analysis programs emerged EPEDAT (Early Post-earthquake Damage Assessment Tool) and HAZUS (HAZards United States). The EPEDAT development was supported by California OES (Eguchi et al., 1997) but appears to have fallen into desuetude with the further development of HAZUS.

HAZUS. HAZUS is probably somewhat familiar to readers of this document – it currently is the only free software with the ability to perform end-to-end multihazard catastrophe loss modeling, and permits relatively quick and easy estimates of potential seismic (and now flood and wind) losses, including social and indirect economic impacts, for any community in the U.S. The estimates can easily be modified for various mitigation strategies, and the results can be used for mitigation and emergency response planning. The results are clearly communicated in map and tabular formats. HAZUS is gradually winning adoption within state and local governments for planning and emergency response purposes, and is a substantial contribution to national earthquake hazards reduction (the reader is referred to Appendix I, Kircher et al. 2006, and Scawthorn et al. 2006 for more detail).

Other software. Several programs similar in some ways to HAZUS have been developed or are being developed. These include:

- **CATS:** Developed for the Defense Threat Reduction Agency (DTRA) and the Federal Emergency Management Agency (FEMA) by SAIC, CATS is available to Federal, State, and local government emergency response organizations nationwide, and includes models for data fusion analysis that supports disaster and other emergency management. It also treats some technological hazards. (http://cats.saic.com/cats/models/cats_earthquake.html)

- **EXTREMUM** was developed for the Russian Ministry of Extreme Situations. It is GIS-based, has a global default inventory on various scales, seismic hazard/seismic zoning and microzoning maps, elements at risk/population, buildings and structures, lifeline systems, hazardous facilities and algorithms for combining the parameters of mathematical models for estimation of population distribution, buildings' damage and damage distribution, human casualty, etc. A version of *EXTREMUM* is *QUAKELOSS* (www.wapmerr.org/publications.html).

- *LESSLOSS* is a European Integrated Project focusing on Risk Mitigation for Earthquakes and Landslides that relies on the active participation of 46 European partners from both academia and industry. The *LESSLOSS* project addresses research issues on seismic engineering, earthquake risk and impact assessment, landslides monitoring, mapping and management strategies, improved disaster preparedness and mitigation of geotechnical hazards, development of advanced methods for risk assessment, methods of appraising environmental quality and relevant pre-normative research. (www.lessloss.org)

- *NERIES* is a recent EU project that will seek to promote improved access to distributed databases, common protocols, standardized procedures and strategies for long-term archiving and distribution of seismological data; and develop a new generation of hazard and risk assessment tools designed to improve monitoring and understanding of the earthquake process. One of the products is intended to be a HAZUS-like software tool. (<http://www.orfeus-eu.org/neries/NERIES-proposal.htm>).

- *PAGER* (Prompt Assessment of Global Earthquakes for Response) is an automatic system to estimate human impact following significant earthquakes, in development at the USGS (Golden CO). In a sense, it is a global extension of the successful ShakeMaps from hazard to risk. (<http://earthquake.usgs.gov/eqcenter/pager/>).

- *ZEUS-NL* has been developed by the Mid Americas Earthquake Center (MAE) and is a free 3D static and dynamic structural analysis platform for earthquake engineering applications, as well as *MAEviz*, a Consequence-Based Risk Management methodology using a visual, menu-driven system to generate damage estimates from scientific and engineering principles and data, test multiple mitigation strategies, and support modeling efforts to estimate higher level impacts of earthquake hazards, such as impacts on transportation networks, social, or economic systems. It enables policy-makers and decision-makers to ultimately develop risk reduction strategies and implement mitigation actions. (mae.ce.uiuc.edu/software_and_tools/zeus_nl.html).

In other developments, the UN IDNDR several years ago funded the RADIUS (Risk Assessment Tools for Diagnosis of Urban Areas against Seismic Disasters, see <http://www.geohaz.org/radius/RADIUSIntro.htm>) project, a spreadsheet-based earthquake

loss estimation tool. It suffers from a distinctly inferior technology to HAZUS, and distribution limitations, despite its claim to be freely available.

Discussion. A number of valuable risk-modeling tools currently exist, but appear to be ill suited for research to examine the societal impacts of new knowledge or alternative approaches in earth science, geotechnical and structural engineering, and disaster social sciences. Many of the models follow the LE (i.e., empirical) approach, although PBEE technology is increasingly being adopted. The most advanced models are proprietary and confidential, and only available at significant cost. While HAZUS is distributed free of charge, its adoption has been modest to date, for various reasons and despite excellent documentation of its methodologies. HAZUS has required a significant investment on the part of FEMA, and major changes to the platform, such as to permit incorporation of physics-based modeling of ground motion, are likely to be painfully slow. Currently, there is no risk analysis software freely available and readily adaptable to advances in technology.

Informed by the lessons and limitations of existing risk-modeling software, the next section provides a mission statement for OpenRisk (modeled after OpenSHA's mission statement).

2.2 MISSION STATEMENT

OpenRisk is an effort to develop object-oriented, web- and GUI-enabled, open-source, and freely available software code for conducting multihazard risk analysis. The resulting body of code and applications is also referred to as OpenRisk.

OpenRisk's goal is to provide a framework where any arbitrarily complex model of hazard, vulnerability, and loss can "plug in" for analysis without having to change what's being plugged into. *Hazard* refers to the effects of natural and other phenomena (e.g., earthquakes, tropical cyclones) that can lead to damaging impacts on the built and social environments. By *vulnerability* is meant the relationship between these effects and loss through damage to the built and social environment. An example of a vulnerability function would be repair cost for a particular category of buildings, as a function of damped elastic spectral acceleration response. *Loss* refers to the undesirable financial and social impacts

resulting from damage. Examples of loss are repair costs, casualties, and loss of use (i.e., dollars, deaths, and downtime).

OpenRisk applications may be stand-alone or may be distributed over the Internet in what the OpenSHA developers refer to as a community modeling environment, all tied together with a user-friendly web interface.

The purpose of developing OpenRisk is to provide researchers with tools to perform and incrementally improve quantitative study in any of the domains of risk modeling, and to enable them to explore the risk implications of new knowledge, without requiring universal mastery of all the relevant scientific, engineering, and social-science disciplines. Toward that end, OpenRisk is intended to comprise open-source software using open-source software licenses such as those distributed by the Open Source Initiative (<http://www.opensource.org/>), and participation from anyone in this development is welcome.

2.3 DEVELOPMENT APPROACH

OpenRisk is envisaged as being developed in an open framework – that is, without close hierarchical centralized management. Nevertheless, OpenRisk will not be created in a vacuum. Rather, OpenRisk is envisaged as being created in a web-based collaboratory, by a community of researchers whose efforts are coordinated via a group representing the community (AGORA, discuss further below). For a discussion of the nature of open-source software, see http://en.wikipedia.org/wiki/Open_source; for more detail, see the Open Source Initiative website (<http://opensource.org/>). In summary, open source is a well established approach to software development, which has produced the *Linux* kernel, *Apache* (HTTP web server), *Mozilla Firefox* (web browser), the *OpenOffice* office suite (a free competitor to MS Office, with similar features) and *Mediawiki* (which runs *Wikipedia*). The basic idea behind open source

... is very simple: When programmers can read, redistribute, and modify the source code for a piece of software, the software evolves. People improve it, people adapt it, people fix bugs. And this can happen at a speed that, if one is used to the slow pace of conventional software development, seems astonishing. We in the open source community have learned that this rapid evolutionary process produces better software than the traditional closed model, in which only a very few programmers can see the

source and everybody else must blindly use an opaque block of bits.
(<http://opensource.org/>)

2.4 OPENRISK PROJECT MANAGEMENT

The vision is that OpenRisk development will occur via OpenRisk needs being identified, and efforts coordinated, among a community of researchers. Communication and coordination of efforts by this community will be facilitated by a new organization, AGORA (Alliance for Global Open Risk Analysis), which has recently been created and is having its first international workshop at Caltech Feb. 27-28, 2007 (see www.risk-agera.org). AGORA's goal is the fostering of open risk analysis – that is, development and dissemination of open and transparent risk analysis methods and tools, particularly open-source risk-analysis software.

OpenRisk is anticipated as AGORA's initial project, and its development will be facilitated and managed via AGORA web discussions, OpenRisk modules being posted to the AGORA website and vetted by AGORA members. The potential advantages of open source development of OpenRisk is rapid development at modest cost, with users needs being identified by the user community in near real-time. The primary disadvantage is the uncertainty as to when development will occur, by whom and, indeed, whether a community will actually even coalesce and develop OpenRisk.

2.5 DEVELOPMENT TIMELINE

Given the above vision for OpenRisk development, a crisp timeline clearly cannot be laid down. However, there are a number of encouraging developments such that the following timeline is plausible:

Table 1. Timeline for development of OpenRisk

Event	Time	Comment
Initial design	2007	This design document
AGORA Workshop	2007	Workshop Feb 27-28, Caltech
OpenRisk 1.0 β	2007	Single-site BCR and LE applications, a fragility function calculator, a portfolio import tool, and a portfolio EAL calculator
AGORA meeting	Sept 2007	Italy
Launch OpenRisk 1.0	2008	Launch OpenRisk at 14WCEE (Beijing)
OpenRisk 1.5*	2008-2009	Further OpenRisk applications: arbitrary gridded hazard, portfolio earthquake loss exceedance frequency calculator, enhanced vulnerability catalog
OpenRisk 2.0	2009-2010	Large-portfolio speed enhancements
AGORA meeting	2009	tbd
OpenRisk 2.0	2010	Full actuarial quality portfolio seismic loss analysis capability
AGORA meeting	2010	tbd
OpenRisk 3.0	2011	Extension to other hazards (tropical cyclone, flood)

* Intermediate releases will be offered as frequently as outside contributions are made

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3 SINGLE-FACILITY RISK ALGORITHMS

This chapter presents risk-calculation algorithms that can be coded into OpenRisk software. It is restricted to single facilities such as a single building or bridge. For groups of facilities, or *portfolios*, see Chapter 4.

Throughout this chapter, vectors are arrays denoted by $\{x\}$. Unless noted otherwise, the index to vectors is denoted by i ; the first member of a vector is denoted with $i=1$, and the size of the vector is denoted by m . Unless noted otherwise, the index to a rectangular array is the pair (i,j) , with rows indexed by i , columns indexed by j , the number of rows denoted by m , and the number of columns by n , and valid indexes are $1 \leq i \leq m$ and $1 \leq j \leq n$. Portions of this chapter are taken from Porter et al. (2004), with some notational changes.

3.1 FACILITY EAL FROM VULNERABILITY AND HAZARD

Definition of the vulnerability function and hazard function. Let $y(s)$ denote a mean vulnerability function, defined as the mean damage factor repair cost divided by replacement cost new, for a building or other facility as a function of intensity, denoted by s . Here, the intensity s is limited nonnegative scalar values. Let IMT denote the intensity measure type of s . Let $G(s)$ denote the mean hazard function for the facility site, defined as the mean annual rate at which events occur causing intensity equal to or greater than s , as a function of s . Let V denote the replacement cost of the facility.

In most practical situations, the vulnerability function $y(s)$ and hazard function $G(s)$ would be evaluated at a set of intensity values s_0, s_1, \dots, s_m . The present calculations address the case where $y(s)$ and $G(s)$ are available at the same m values s_1, s_2, \dots, s_m . For brevity, let us denote $y(s_1), y(s_2), \dots, y(s_m)$ etc. y_1, y_2, \dots, y_m , and let us similarly denote $G(s_1), G(s_2), \dots, G(s_m)$ by G_1, G_2, \dots, G_m , respectively. A value y_i is referred to here as the mean damage factor given shaking intensity s_i . A value G_i is referred to here as the mean exceedance frequency of shaking intensity s_i .

The values of y , G , and s can be stored in vectors of size m .

It is assumed here that $G(s)$ varies exponentially between values of s , i.e.,

$$G(s) = G_{i-1} \exp(g_i (s - s_i)) \quad \text{for } s_{i-1} < s < s_i \quad (1)$$

where g_i is constant for $s_{i-1} < s < s_i$. (It is the slope in the log-linear domain of the mean hazard function.) That is,

$$G = \exp\left(\ln G_{i-1} + \frac{(s - s_{i-1})}{(s_i - s_{i-1})}(\ln G_i - \ln G_{i-1})\right) \quad (2)$$

where G is the mean exceedance rate of shaking intensity s , where $s_{i-1} \leq s < s_i$, G_{i-1} denotes the mean exceedance rate of s_{i-1} , and G_i denotes the mean exceedance rate of s_i . One can estimate g_i as

$$g_i = \frac{\ln(G_i/G_{i-1})}{\Delta s_i} \quad i = 2, 3, \dots, m \quad (3)$$

where

$$\Delta s_i = s_i - s_{i-1} \quad i = 2, 3, \dots, m \quad (4)$$

It is assumed here that the vulnerability function varies linearly between values of s , i.e.,

$$y(s) = y_{i-1} + \frac{\Delta y_i}{\Delta s_i}(s - s_{i-1}) \quad \text{for } s_{i-1} < s < s_i \quad (5)$$

where

$$\Delta y_i = y_i - y_{i-1} \quad i = 2, 3, \dots, m \quad (6)$$

Then EAL is given by

$$\begin{aligned} EAL &= V \sum_{i=2}^m \left(\int_0^{\Delta s_i} \left(y_{i-1} + \frac{\Delta y_i}{\Delta s_i} \tau \right) (-g_i G_{i-1} \exp(g_i \tau)) d\tau \right) + R \\ &= V \sum_{i=2}^m \left(-y_{i-1} G_{i-1} \exp(g_i \tau) \Big|_{\tau=0}^{\Delta s_i} - \frac{\Delta y_i}{\Delta s_i} G_{i-1} \left(\exp(g_i \tau) \left(\tau - \frac{1}{g_i} \right) \right) \Big|_{\tau=0}^{\Delta s_i} \right) + R \\ &= V \sum_{i=2}^m \left(y_{i-1} G_{i-1} (1 - \exp(g_i \Delta s_i)) - \frac{\Delta y_i}{\Delta s_i} G_{i-1} \left(\exp(g_i \Delta s_i) \left(\Delta s_i - \frac{1}{g_i} \right) + \frac{1}{g_i} \right) \right) + R \end{aligned} \quad (7)$$

where R is a remainder term for values of $s > s_m$, and has an upper bound of $VG(s_m)$, and where

$$\tau = s - s_{i-1} \quad s_{i-1} < s < s_i \quad (8)$$

For large s_m , R can be neglected.

Example 1. Consider a building at 34.159N, 118.126W, with $V_{S30} = 360$ m/sec, replacement cost $V = \$115,000$ and hazard function P as shown in Table 2, expressed in terms of probability of exceeding various values of $S_a(0.2 \text{ sec}, 5\%)$ in 30 years. The vulnerability function for the building (mean damage factor as a fraction of V) is shown in Table 3, in the column labeled y . Also consider a possible retrofit of the building, with post-retrofit vulnerability function shown in Table 3 in the column labeled y_r . Both vulnerability functions are expressed as a function of 5%-damped, 0.2-sec spectral acceleration response (units of g). Calculate EAL for the as-is and retrofitted conditions.

Note that in this example, the hazard was calculated using the earthquake rupture forecast offered by WGCEP UCERF 1.0 (2006); Frankels' fault model; an incremental rupture offset of 5.0 km, excluding background seismicity; including time dependence; Campbell and Bozorgnia's (2006) attenuation relationship; no Gaussian truncation, the random horizontal component (actually inconsistent with the vulnerability function, which is tabulated for geometric mean, but good enough for illustration purposes), total standard deviation, and 1.0 km depth to 2.5 km/sec shearwave velocity.

Solution: Begin by calculating hazard in mean events per year. Assuming Poisson arrivals, the mean exceedance frequency G , in events per year, is given by

$$G = -\ln(1 - P)/T \quad (9)$$

where P is the exceedance probability in T years. For example, if $P = 0.9955$, $G = -\ln(1 - 0.9955)/30 = 0.180$. The result of this calculation is shown in Table 2. Next interpolate G at the values of S_a at which the vulnerability function is calculated. Results are shown in Table 3. For example, considering $G(s = 0.3)$, referring to Table 2, $s_{i-1} = 0.251g$, $G_{i-1} = 0.0380$, $s_i = 0.316g$, $G_i = 0.0272$, and thus by Equation (2), $G = \exp(\ln(0.0380) + (0.3 - 0.251)/(0.316 - 0.251) \times (\ln(0.0272) - \ln(0.0380))) = 0.030$, as shown in Table 3 in the column labeled G .

Next calculate g , Δs , Δy , and Δy_r according to Equations (3), (4), (6) and (6), respectively, for $i = 2, 3, \dots m$. For example, $\Delta s_2 = 0.2 - 0.1 = 0.1$, $g_2 = \ln(G_2/G_1)/\Delta s_2 = \ln(0.0514/0.1034)/0.1 = -6.99$, $\Delta y_2 = 0.011 - 0.003 = 0.008$, and $\Delta y_{r2} = 0.000 - 0.000 = 0.000$. Results for $m = 3, 4, \dots 20$ are shown in the table. The summand of Equation (7) is denoted q for the as-is condition and q_r for the retrofitted condition. For example,

$$\begin{aligned}
 q_2 &= y_1 G_1 (1 - \exp(g_2 \Delta s_2)) - \frac{\Delta y_2}{\Delta s_2} G_1 \left(\exp(g_2 \Delta s_2) \left(\Delta s_2 - \frac{1}{g_2} \right) + \frac{1}{g_2} \right) \\
 &= 0.003 \cdot 0.1034 \cdot (1 - \exp(-6.99 \cdot 0.1)) - \frac{0.008}{0.1} \cdot 0.1034 \cdot \left(\exp(-6.99 \cdot 0.1) \left(0.1 - \frac{1}{-6.99} \right) + \frac{1}{-6.99} \right) \\
 &= 0.00034
 \end{aligned}$$

$$\begin{aligned}
 q_{r3} &= y_{r2} G_2 (1 - \exp(g_3 \Delta s_3)) - \frac{\Delta y_{r3}}{\Delta s_3} \cdot G_2 \left(\exp(g_3 \Delta s_3) \left(\Delta s_3 - \frac{1}{g_3} \right) + \frac{1}{g_3} \right) \\
 &= 0.000 \cdot 0.0514 \cdot (1 - \exp(-5.53 \cdot 0.1)) - \frac{0.002}{0.1} \cdot 0.0514 \cdot \left(\exp(-5.53 \cdot 0.1) \left(0.1 - \frac{1}{-5.53} \right) + \frac{1}{-5.53} \right) \\
 &= 0.00002
 \end{aligned}$$

Denoting the as-is and post-retrofit expected annualized loss respectively by EAL and EAL_r , they are given by $EAL = V \times \Sigma q = \$115,000 \times 0.00359 = \412 and $EAL_r = V \times \Sigma q_r = \$115,000 \times 0.00130 = \149 .

Table 2. Hazard for Example 1: 30-year exceedance probability of $S_a(0.2)$

S_a, g	P	G	S_a, g	P	G	S_a, g	P	G
1.00E-04	0.9955	0.1800	5.01E-03	0.9955	0.1800	3.16E-01	0.5577	0.0272
1.30E-04	0.9955	0.1800	6.31E-03	0.9955	0.1800	3.98E-01	0.4341	0.0190
1.60E-04	0.9955	0.1800	7.94E-03	0.9955	0.1799	5.01E-01	0.3224	0.0130
2.00E-04	0.9955	0.1800	1.00E-02	0.9954	0.1797	6.31E-01	0.2296	0.0087
2.50E-04	0.9955	0.1800	1.26E-02	0.9954	0.1793	7.94E-01	0.1569	0.0057
3.20E-04	0.9955	0.1800	1.59E-02	0.9952	0.1783	1.00E+00	0.1021	0.0036
4.00E-04	0.9955	0.1800	2.00E-02	0.9950	0.1765	1.26E+00	0.0625	0.0022
5.00E-04	0.9955	0.1800	2.51E-02	0.9945	0.1733	1.58E+00	0.0355	0.0012
6.30E-04	0.9955	0.1800	3.16E-02	0.9936	0.1682	2.00E+00	0.0185	0.0006
7.90E-04	0.9955	0.1800	3.98E-02	0.9919	0.1606	2.51E+00	0.0088	0.0003
1.00E-03	0.9955	0.1800	5.01E-02	0.9890	0.1502	3.16E+00	0.0037	0.0001
1.26E-03	0.9955	0.1800	6.31E-02	0.9835	0.1369	3.98E+00	0.0014	0.0000
1.58E-03	0.9955	0.1800	7.94E-02	0.9735	0.1211	5.01E+00	0.0005	0.0000
2.00E-03	0.9955	0.1800	1.00E-01	0.9551	0.1034	6.31E+00	0.0001	0.0000
2.51E-03	0.9955	0.1800	1.26E-01	0.9223	0.0852	7.94E+00	0.0000	0.0000
3.16E-03	0.9955	0.1800	1.58E-01	0.8681	0.0675	1.00E+01	0.0000	0.0000
3.98E-03	0.9955	0.1800	2.00E-01	0.7870	0.0515	3.16E-01	0.5577	0.0272

Table 3. Example 1 EAL calculation

s	y	y_r	G	g	Δy	Δy_r	q	q_r
0.1	0.003	0.000	0.10344					
0.2	0.011	0.000	0.05141	-6.99	0.008	0.000	0.00034	0.00000
0.3	0.043	0.002	0.02957	-5.53	0.032	0.002	0.00056	0.00002
0.4	0.070	0.020	0.01884	-4.50	0.027	0.018	0.00059	0.00011
0.5	0.090	0.037	0.01303	-3.69	0.020	0.017	0.00046	0.00016
0.6	0.107	0.053	0.00957	-3.09	0.017	0.016	0.00034	0.00015
0.7	0.121	0.068	0.00727	-2.75	0.014	0.015	0.00026	0.00014
0.8	0.133	0.082	0.00562	-2.58	0.012	0.014	0.00021	0.00012
0.9	0.144	0.094	0.00449	-2.24	0.011	0.012	0.00016	0.00010
1.0	0.154	0.106	0.00359	-2.24	0.010	0.012	0.00013	0.00009
1.1	0.163	0.117	0.00294	-1.98	0.009	0.011	0.00010	0.00007
1.2	0.171	0.127	0.00242	-1.98	0.008	0.010	0.00009	0.00006
1.3	0.178	0.136	0.00200	-1.89	0.007	0.009	0.00007	0.00005
1.4	0.185	0.143	0.00167	-1.78	0.007	0.007	0.00006	0.00005
1.5	0.191	0.150	0.00140	-1.78	0.006	0.007	0.00005	0.00004
1.6	0.197	0.156	0.00118	-1.75	0.006	0.006	0.00004	0.00003
1.7	0.203	0.160	0.00100	-1.61	0.006	0.004	0.00003	0.00003
1.8	0.208	0.164	0.00085	-1.61	0.005	0.004	0.00003	0.00002
1.9	0.213	0.167	0.00073	-1.61	0.005	0.003	0.00003	0.00002
2.0	0.218	0.169	0.00062	-1.60	0.005	0.002	0.00002	0.00002
						$\Sigma =$	0.00359	0.00130
						EAL =	\$412	\$149

3.2 FACILITY EAL FROM DAMAGE PROBABILITY MATRIX AND HAZARD

Definition of the damage probability matrix. The damage probability matrix contains a different depiction of facility vulnerability: a probability mass function of damage factor for each of several levels of intensity. Let z_i denote a particular value of the uncertain damage factor Y . (Damage factor is defined here as repair cost as a fraction of replacement cost new). The value z_i is stored in element i of a vector of size m , where $i \in \{1, 2, \dots, m\}$ and $0 < z_i < z_{i+1}$ for all $1 \leq i < m$.

Let s_j denote a nonnegative scalar intensity measure, stored in element j of a vector of size n , where $j \in \{1, 2, \dots, n\}$, constrained by $0 < s_j < s_{j+1}$ for all $1 < j < n$. Let IMT denote the intensity measure type (e.g., PGA, PGV, etc.) of s .

Let Y_j denote the uncertain damage factor given the occurrence of intensity s_j .

Let $P[]$ denote the probability of the condition inside the brackets.

Let p_{ij} denote the probability

$$\begin{aligned} p_{ij} &= P[z_i \leq Y_j < z_{i+1}] & 1 \leq i < m \\ &= P[z_i \leq Y_j] & i = m \end{aligned} \quad (10)$$

And let p_{ij} be stored in element ij of a rectangular matrix of size $m \times n$, and constrained by

$$\begin{aligned} 0 \leq p_{ij} &\leq 1.0 \\ \sum_{i=1}^m p_{ij} &\leq 1.0 \end{aligned} \quad (11)$$

Note there is an implicit assumption that there can be a nonzero $P[Y_j < z_1]$, given by

$$P[Y_j < z_1] = 1 - \sum_{i=1}^m p_{ij} \quad (12)$$

This remaining probability is assumed hereafter to refer to the probability of (effectively) zero damage. The matrix $\{p\}$ is referred to here as the damage probability matrix (DPM). Let y_j denote the mean damage factor conditioned on the occurrence of intensity s_j , calculated as

$$y_j = \sum_{i=1}^{m-1} \left(p_{ij} \left(\frac{z_i + z_{i+1}}{2} \right) \right) + p_{mj} \left(\frac{z_m + 1}{2} \right) \quad (13)$$

which implicitly assumes a maximum damage factor of 1.0. The values of y_j are stored in a vector of size n . EAL can now be calculated as in Section 3.1, Facility EAL from vulnerability and hazard, with the exception that $\{s\}$, $\{y\}$, and $\{G\}$ are vectors of size n and are indexed by j rather than i . This change of index is made to accommodate the convention of arranging a DPM with rows corresponding to varying levels of damage factor and columns corresponding to varying levels of intensity. To change that arrangement for programming convenience would lead to confusion by the user.

Note that the only new approximation made here is in Equation (13), which implicitly assumes that Y_j is piecewise uniformly distributed between values of z , given s_j . This assumption follows the precedent of ATC-13 (Applied Technology Council 1985), and is also consistent with the maximum-entropy distribution (in the sense of information theory) for a random variable whose only constraint is that it is bounded above and below.

Example 2. Consider the building in the previous example, whose vulnerability function is depicted via the DPM in Table 8. Also consider a possible retrofit of the building, with post-retrofit vulnerability function shown in Table 9. Both DEMs are expressed as the probability of exceeding the damage factor shown in the row header, as a function of the 5%-damped, 0.2-sec spectral acceleration response (units of g) shown in the column header. Calculate *EAL* for the as-is and retrofitted conditions.

Table 4. DPM for example 2 as-is building

DF	Sagm(0.2sec, 5%), g									
	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
0.001	0.192	0.147	0.036	0.004	0.001	0.000	0.000	0.000	0.000	0.000
0.002	0.098	0.107	0.041	0.008	0.002	0.000	0.000	0.000	0.000	0.000
0.003	0.098	0.144	0.081	0.025	0.007	0.002	0.001	0.000	0.000	0.000
0.005	0.047	0.092	0.072	0.032	0.012	0.005	0.002	0.001	0.000	0.000
0.007	0.036	0.089	0.091	0.053	0.026	0.012	0.006	0.003	0.001	0.001
0.010	0.039	0.133	0.202	0.169	0.115	0.073	0.046	0.029	0.018	0.012
0.020	0.010	0.051	0.117	0.134	0.117	0.094	0.072	0.055	0.040	0.030
0.030	0.006	0.041	0.127	0.179	0.189	0.179	0.160	0.140	0.119	0.102
0.050	0.002	0.016	0.066	0.109	0.132	0.141	0.142	0.137	0.130	0.121
0.070	0.001	0.010	0.054	0.097	0.128	0.148	0.161	0.167	0.170	0.168
0.100	0.001	0.009	0.062	0.122	0.174	0.219	0.256	0.286	0.313	0.332
0.200	0.000	0.002	0.018	0.036	0.053	0.070	0.086	0.100	0.115	0.128
0.300	0.000	0.001	0.011	0.021	0.031	0.041	0.050	0.060	0.069	0.078
0.500	0.000	0.000	0.003	0.006	0.008	0.010	0.013	0.015	0.017	0.019
0.700	0.000	0.000	0.002	0.003	0.004	0.004	0.005	0.006	0.006	0.007
1.000	0.000	0.000	0.001	0.002	0.002	0.002	0.002	0.002	0.002	0.003

Table 5. DPM for example 2 retrofitted building

DF	S _{gm} (0.2sec, 5%), g									
	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
0.001	0.000	0.000	0.176	0.098	0.054	0.018	0.005	0.001	0.000	0.000
0.002	0.000	0.000	0.080	0.084	0.054	0.024	0.009	0.003	0.001	0.000
0.003	0.000	0.000	0.073	0.130	0.096	0.056	0.028	0.012	0.005	0.002
0.005	0.000	0.000	0.032	0.094	0.080	0.057	0.034	0.019	0.010	0.005
0.007	0.000	0.000	0.023	0.100	0.095	0.079	0.056	0.036	0.022	0.012
0.010	0.000	0.000	0.023	0.176	0.194	0.199	0.174	0.138	0.104	0.074
0.020	0.000	0.000	0.005	0.080	0.105	0.129	0.134	0.126	0.112	0.095
0.030	0.000	0.000	0.003	0.073	0.110	0.151	0.177	0.188	0.188	0.180
0.050	0.000	0.000	0.001	0.032	0.056	0.083	0.106	0.124	0.135	0.141
0.070	0.000	0.000	0.000	0.023	0.044	0.070	0.094	0.116	0.133	0.148
0.100	0.000	0.000	0.000	0.023	0.051	0.083	0.117	0.152	0.184	0.217
0.200	0.000	0.000	0.000	0.005	0.014	0.024	0.034	0.045	0.057	0.069
0.300	0.000	0.000	0.000	0.003	0.009	0.014	0.020	0.027	0.033	0.040
0.500	0.000	0.000	0.000	0.001	0.003	0.004	0.006	0.007	0.009	0.010
0.700	0.000	0.000	0.000	0.000	0.001	0.002	0.003	0.003	0.004	0.004
1.000	0.000	0.000	0.000	0.000	0.001	0.001	0.002	0.002	0.002	0.002

Solution. Begin by calculating y for the as-is and retrofitted conditions, according to Equation (13). These results are shown in Table 6. Sample calculation is omitted for brevity. The rest of the calculation of EAL proceeds as in the example of Section 3.1; results are shown in Table 7.

Table 6. Mean damage factor vs. $S_a(0.2 \text{ sec}, 5\%)$, units of g, for example 2 buildings

	S _{gm} (0.2sec, 5%), g									
	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
y	0.003	0.011	0.044	0.072	0.093	0.111	0.125	0.138	0.149	0.159
y_r	0.000	0.000	0.002	0.021	0.038	0.054	0.070	0.085	0.097	0.110

Table 7. Example 2 EAL calculation

s	y	y_r	G	g	Δy	Δy_r	q	q_r
0.1	0.003	0.000	0.10344					
0.2	0.011	0.000	0.05141	-6.99	0.008	0.000	0.00035	0.00000
0.3	0.044	0.002	0.02957	-5.53	0.033	0.002	0.00057	0.00002
0.4	0.072	0.021	0.01884	-4.50	0.028	0.019	0.00061	0.00011
0.5	0.093	0.038	0.01303	-3.69	0.021	0.017	0.00048	0.00017
0.6	0.111	0.054	0.00957	-3.09	0.018	0.017	0.00035	0.00016
0.7	0.125	0.070	0.00727	-2.75	0.015	0.016	0.00027	0.00014
0.8	0.138	0.085	0.00562	-2.58	0.012	0.015	0.00022	0.00013
0.9	0.149	0.097	0.00449	-2.24	0.011	0.013	0.00016	0.00010
1.0	0.159	0.110	0.00359	-2.24	0.010	0.013	0.00014	0.00009
						$\Sigma =$	0.00314	0.00092
						EAL =	\$361	\$106

3.3 FACILITY EAL FROM DAMAGE EXCEEDANCE MATRIX AND HAZARD

Definition of the damage exceedance matrix. Yet another depiction of facility vulnerability, containing essentially the same information as the damage probability matrix, is the *damage exceedance matrix* (DEM). Recall that the DPM is a set of probability mass functions for damage factor given intensity. The DEM instead depicts the complement of the cumulative distribution function. To be precise, the DEM is a rectangular matrix with m rows and n columns, whose columns reflect particular intensity levels and whose rows reflect particular values of the damage factor. The entries of the DEM give the probability that the uncertain damage factor will exceed a particular value (the row header), when the facility is exposed to a given intensity level (the column header). Let i denote the row index, and let j denote the column index, i.e., $i \in \{1, 2, \dots, m\}$ and $j \in \{1, 2, \dots, n\}$. Let z_i denote the value of the damage factor for row i , and let s_j denote the value of intensity for column j . Let Y_j denote the uncertain damage factor given intensity s_j . Let P denote probability, and let q_{ij} denote the entry of the DEM in row i , column j , i.e., the probability

$$q_{ij} = P[Y_j \geq z_i] \quad (14)$$

stored in element ij of a rectangular matrix of size $m \times n$, and constrained by

$$\begin{aligned}
s_{j+1} &> s_j \\
z_{i+1} &> z_i \\
0 &\leq q_{ij} \leq 1.0 \\
q_{ij} &\geq q_{i+1,j} \\
q_{ij} &\leq q_{i,j+1}
\end{aligned} \tag{15}$$

Given the DEM, the DPM is calculated by noting that

$$\begin{aligned}
p_{ij} &= P[Y_j \geq z_i] - P[Y_j \geq z_{i+1}] & 1 \leq i < m \\
&= q_{ij} - q_{i+1,j} & 1 \leq i < m \\
&= P[Y_j \geq z_i] & i = m \\
&= q_{ij} & i = m
\end{aligned} \tag{16}$$

The value of EAL is then calculated as in Section 3.2, Facility EAL from damage probability matrix and hazard.

Example 3. Consider the building in the previous example, whose vulnerability function is depicted via the DEM in Table 8. Also consider a possible retrofit of the building, with post-retrofit vulnerability function shown in Table 9. Both DEMs are expressed as the probability of exceeding the damage factor shown in the row header, as a function of the 5%-damped, 0.2-sec spectral acceleration response (units of g) shown in the column header. Calculate *EAL* for the as-is and retrofitted conditions.

Table 8. DEM for example 3 as-is building

DF	Sagm(0.2sec, 5%), g									
	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
0.001	0.531	0.841	0.984	0.999	1.000	1.000	1.000	1.000	1.000	1.000
0.002	0.339	0.694	0.947	0.995	0.999	1.000	1.000	1.000	1.000	1.000
0.003	0.241	0.587	0.906	0.987	0.998	1.000	1.000	1.000	1.000	1.000
0.005	0.143	0.443	0.825	0.962	0.991	0.998	0.999	1.000	1.000	1.000
0.007	0.096	0.351	0.753	0.931	0.979	0.993	0.997	0.999	1.000	1.000
0.010	0.059	0.262	0.662	0.878	0.953	0.981	0.992	0.996	0.998	0.999
0.020	0.020	0.130	0.461	0.708	0.838	0.908	0.946	0.967	0.980	0.987
0.030	0.010	0.078	0.344	0.575	0.720	0.814	0.874	0.913	0.940	0.957
0.050	0.003	0.038	0.217	0.396	0.531	0.636	0.714	0.773	0.821	0.855
0.070	0.002	0.022	0.151	0.287	0.399	0.495	0.573	0.635	0.691	0.735
0.100	0.001	0.012	0.097	0.189	0.271	0.347	0.412	0.468	0.521	0.567
0.200	0.000	0.003	0.035	0.067	0.098	0.128	0.156	0.183	0.209	0.234
0.300	0.000	0.001	0.017	0.032	0.045	0.058	0.070	0.082	0.094	0.106
0.500	0.000	0.000	0.006	0.010	0.014	0.017	0.020	0.023	0.025	0.028
0.700	0.000	0.000	0.003	0.005	0.006	0.007	0.007	0.008	0.009	0.010
1.000	0.000	0.000	0.001	0.002	0.002	0.002	0.002	0.002	0.002	0.003

Table 9. DEM for example 3 retrofitted building

DF	Sagm(0.2sec, 5%), g									
	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
0.001	0.000	0.000	0.416	0.923	0.969	0.995	0.999	1.000	1.000	1.000
0.002	0.000	0.000	0.241	0.824	0.915	0.977	0.994	0.999	1.000	1.000
0.003	0.000	0.000	0.161	0.740	0.860	0.953	0.985	0.995	0.999	1.000
0.005	0.000	0.000	0.088	0.611	0.764	0.897	0.958	0.983	0.993	0.997
0.007	0.000	0.000	0.055	0.517	0.684	0.840	0.923	0.964	0.983	0.993
0.010	0.000	0.000	0.032	0.416	0.589	0.761	0.867	0.929	0.962	0.980
0.020	0.000	0.000	0.010	0.241	0.395	0.562	0.693	0.791	0.857	0.906
0.030	0.000	0.000	0.004	0.161	0.290	0.433	0.559	0.665	0.745	0.812
0.050	0.000	0.000	0.001	0.088	0.179	0.282	0.382	0.477	0.557	0.632
0.070	0.000	0.000	0.001	0.055	0.124	0.198	0.276	0.353	0.422	0.491
0.100	0.000	0.000	0.000	0.032	0.079	0.129	0.182	0.237	0.289	0.343
0.200	0.000	0.000	0.000	0.010	0.029	0.046	0.065	0.085	0.104	0.126
0.300	0.000	0.000	0.000	0.004	0.014	0.022	0.031	0.039	0.048	0.057
0.500	0.000	0.000	0.000	0.001	0.005	0.008	0.010	0.013	0.015	0.017
0.700	0.000	0.000	0.000	0.001	0.003	0.004	0.004	0.005	0.006	0.006
1.000	0.000	0.000	0.000	0.000	0.001	0.001	0.002	0.002	0.002	0.002

Solution. The DPMs calculated from Table 8 and Table 9 using Equation (16) are as shown in the previous example, Table 4 and Table 5, respectively. For example, in the as-is case, $p_{11} = q_{11} - q_{21} = 0.531 - 0.339 = 0.192$, which result agrees with Table 4. In the

retrofitted case, $p_{23} = q_{23} - q_{33} = 0.241 - 0.161 = 0.080$, which result agrees with Table 5. The result is therefore the same as in the previous example.

3.4 VULNERABILITY CONVERSIONS

It is sometimes useful to convert between depictions of vulnerability. Section 3.3 showed in Equation (16) how to calculate the DPM from the DEM. We now consider additional useful conversions between depictions of vulnerability.

Facility DEM from vulnerability function. Now consider how to create DEMs from vulnerability functions. The following uses the notation shown in Section 3.1 for vulnerability functions and Section 3.3 for DEMs.

GIVEN:

s_j = shaking intensity indexed by j (e.g., $Sa(0.2 \text{ sec}, 5\%) = 0.1g, 0.2g, \dots 2g$)

y_j = mean damage factor given shaking s_j

d_j = coefficient of variation of damage factor given shaking s_j

REQUIRED:

q_{ij} = probability of exceeding damage factor z_i given shaking s_j , under conditions:

- (a) Damage factor given s_j is lognormally distributed
- (b) Damage factor given s_j is normally distributed and truncated at zero (i.e., with a probability mass at zero damage factor whose value equals the normal CDF evaluated at zero damage factor)
- (c) Damage factor given s_j is arbitrarily distributed

SOLUTION:

(a) Damage factor given s_j is lognormally distributed. Denoting

Φ = standard normal (Gaussian) cumulative distribution function

θ_j = median damage factor given shaking s_j

b_j = logarithmic standard deviation of damage factor given shaking s_j

Then

$$\theta_j = \frac{y_j}{\sqrt{1+d_j^2}} \quad (17)$$

$$b_j = \sqrt{\ln(1+d_j^2)} \quad (18)$$

$$\begin{aligned} q_{ij} &= 0 & y_j &= 0, z_i > 0 \\ &= 1 - \Phi\left(\frac{\ln(z_i/\theta_j)}{b_j}\right) & y_j &> 0 \end{aligned} \quad (19)$$

(b) Damage factor given s_j is normally distributed and truncated at zero damage factor

$$\begin{aligned} q_{ij} &= 0 & y_j &= 0, z_i > 0 \\ &= 1 - \Phi\left(\frac{z_i - y_j}{d_j y_j}\right) & y_j &> 0 \end{aligned} \quad (20)$$

(c) Damage factor given s_j is arbitrarily distributed. Denoting

$F_{Y_j}(z_i) = P[Y_j \leq z_i]$, i.e., the probability that the damage factor at intensity s_j is less than or equal to z_i

$$q_{ij} = 1 - F_{Y_j}(z_i) \quad (21)$$

Example 4. Consider the same as-is building of the previous examples. The vulnerability information s , y , and d , are as shown in Table 10. Calculate the DEM for $z = 0.001, 0.002, 0.003, 0.005, 0.007, 0.01, 0.02, 0.03, 0.05, 0.07, 0.1, 0.2, 0.3, 0.5, 0.7$, and 1.0 .

Solution. First calculate θ and b according to Equations (17) and (18). These results are shown in the last two rows of Table 10. For example,

$$\begin{aligned} \theta_1 &= \frac{0.003}{\sqrt{1+2.5^2}} \\ &= 0.001114 \\ b_1 &= \sqrt{\ln(1+2.5^2)} \\ &= 1.4075 \end{aligned}$$

as shown (rounded) in the table. Finally, calculate q according to Equation (19). Results are shown in Table 11. For example as shown in the table,

$$q_{11} = 1 - \Phi\left(\frac{\ln(0.001/0.001114)}{1.4075}\right)$$

$$= 0.531$$

Table 10. Example 4 vulnerability information

	Sagm(0.2sec, 5%), g									
	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
<i>y</i>	0.003	0.011	0.043	0.07	0.09	0.107	0.121	0.133	0.144	0.154
<i>d</i>	2.50	2.50	2.24	1.60	1.33	1.18	1.08	1.01	0.95	0.91
θ	0.001	0.004	0.018	0.037	0.054	0.069	0.082	0.094	0.104	0.114
<i>b</i>	1.41	1.41	1.34	1.13	1.01	0.93	0.88	0.84	0.80	0.78

Table 11. Example 4 damage exceedance matrix results

<i>z</i>	Sagm(0.2sec, 5%), g									
	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
0.001	0.531	0.841	0.984	0.999	1.000	1.000	1.000	1.000	1.000	1.000
0.002	0.339	0.694	0.947	0.995	0.999	1.000	1.000	1.000	1.000	1.000
0.003	0.241	0.587	0.906	0.987	0.998	1.000	1.000	1.000	1.000	1.000
0.005	0.143	0.443	0.825	0.962	0.991	0.998	0.999	1.000	1.000	1.000
0.007	0.096	0.351	0.753	0.931	0.979	0.993	0.997	0.999	1.000	1.000
0.010	0.059	0.262	0.662	0.878	0.953	0.981	0.992	0.996	0.998	0.999
0.020	0.020	0.130	0.461	0.708	0.838	0.908	0.946	0.967	0.980	0.987
0.030	0.010	0.078	0.344	0.575	0.720	0.814	0.874	0.913	0.940	0.957
0.050	0.003	0.038	0.217	0.396	0.531	0.636	0.714	0.773	0.821	0.855
0.070	0.002	0.022	0.151	0.287	0.399	0.495	0.573	0.635	0.691	0.735
0.100	0.001	0.012	0.097	0.189	0.271	0.347	0.412	0.468	0.521	0.567
0.200	0.000	0.003	0.035	0.067	0.098	0.128	0.156	0.183	0.209	0.234
0.300	0.000	0.001	0.017	0.032	0.045	0.058	0.070	0.082	0.094	0.106
0.500	0.000	0.000	0.006	0.010	0.014	0.017	0.020	0.023	0.025	0.028
0.700	0.000	0.000	0.003	0.005	0.006	0.007	0.007	0.008	0.009	0.010
1.000	0.000	0.000	0.001	0.002	0.002	0.002	0.002	0.002	0.002	0.003

Facility DEM from DPM. Another conversion between depictions of vulnerability is to calculate the damage exceedance matrix (DEM) from the damage probability matrix (DPM). The damage probability matrix (DPM) is as defined in Section 3.2, Facility EAL from damage probability matrix and hazard. In brief, the DPM is a rectangular $m \times n$ matrix whose

m rows correspond to ranges of the damage factor z , whose n columns correspond to discrete intensity levels s , and each of whose entries p_{ij} denotes the probability that, given that the facility experiences intensity s_j , repairs will cost between z_i and z_{i+1} times the replacement cost of the facility. The entries p_{ij} in the bottom row of the table denote the probability that, given that the facility experiences intensity s_j , repairs will cost between z_i and 1.0 times the replacement cost of the facility.

The DPM will be used to calculate the damage exceedance matrix (DEM), defined in Section 3.3, Facility EAL from damage exceedance matrix and hazard. In brief, the DEM is a rectangular $m \times n$ matrix whose m rows correspond to values of the damage factor z , whose n columns correspond to discrete intensity levels s , and each of whose entries q_{ij} denotes the probability that, given that the facility experiences intensity s_j , repairs will cost *at least* z_i times the replacement cost of the facility. To calculate PML from the DPM and the hazard function, calculate the damage exceedance matrix from the DPM as shown in Equation (22), then calculate PML as shown in Section 3.6, Facility PML from a damage exceedance matrix and hazard.

$$q_{ij} = \sum_{k=i}^m p_{kj}, \text{ for } i = 1, 2, \dots, m \text{ and } j = 1, 2, \dots, n \quad (22)$$

Example 5. Consider the as-is building in the previous examples. Calculate the DEM from the DPM. The DPM is given in Table 4.

Solution. As shown in Table 4, $m = 16$ and $n = 10$. For $1 \leq i \leq 16$ and $1 \leq j \leq 10$, apply Equation (22). For example,

$$\begin{aligned} q_{21} &= 0.098 + 0.098 + 0.047 + 0.036 + 0.039 + 0.01 + 0.006 + 0.002 + 0.001 + 0.001 \\ &= 0.338 \end{aligned}$$

which agrees with Table 8 with some rounding error. The full DEM is shown in Table 12, which can be compared with Table 8; the two tables generally agree within ± 0.001 , with the differences attributable to rounding error.

Table 12. Example 5 result, DEM calculated from DPM

z	Sagm(0.2sec, 5%), g									
	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
0.001	0.530	0.842	0.984	1.000	1.000	1.000	1.000	1.000	1.000	1.000
0.002	0.338	0.695	0.948	0.996	1.000	1.000	1.000	1.000	1.000	1.000
0.003	0.240	0.588	0.907	0.988	0.998	1.000	1.000	1.000	1.000	1.000
0.005	0.142	0.444	0.826	0.963	0.991	0.998	1.000	1.000	1.000	1.000
0.007	0.095	0.352	0.754	0.931	0.979	0.993	0.999	1.000	1.000	1.000
0.01	0.059	0.263	0.663	0.878	0.953	0.981	0.993	0.997	0.999	1.000
0.02	0.020	0.130	0.461	0.709	0.838	0.908	0.947	0.968	0.981	0.988
0.03	0.010	0.079	0.344	0.575	0.721	0.814	0.875	0.913	0.941	0.958
0.05	0.004	0.038	0.217	0.396	0.532	0.635	0.715	0.773	0.822	0.856
0.07	0.002	0.022	0.151	0.287	0.400	0.494	0.573	0.636	0.692	0.735
0.1	0.001	0.012	0.097	0.190	0.272	0.346	0.412	0.469	0.522	0.567
0.2	0.000	0.003	0.035	0.068	0.098	0.127	0.156	0.183	0.209	0.235
0.3	0.000	0.001	0.017	0.032	0.045	0.057	0.070	0.083	0.094	0.107
0.5	0.000	0.000	0.006	0.011	0.014	0.016	0.020	0.023	0.025	0.029
0.7	0.000	0.000	0.003	0.005	0.006	0.006	0.007	0.008	0.008	0.010
1	0.000	0.000	0.001	0.002	0.002	0.002	0.002	0.002	0.002	0.003

3.5 FACILITY PML FROM VULNERABILITY FUNCTION AND HAZARD

The *PML* to a single facility is defined here as the damage factor with probability p_1 of not being exceeded, given the occurrence of an event that has an intensity with probability p_2 of not being exceeded in time T at a given facility. One common set of choices for these values for earthquake PML (though *not required here*) is: $p_1 = p_2 = 0.90$, $T = 50$ yr. The present discussion is restricted to the case where one models events that produce loss at a particular site as a Poisson process. It is further restricted to the case where the conditional probability distribution of the damage factor, given s , is lognormal, with mean value denoted by $y(s)$ and logarithmic standard deviation denoted by $b(s)$. The hazard function is denoted by $G(s)$. The functions $y(s)$, $b(s)$, $G(s)$, are tabulated at a common set of intensity values s_0, s_1, \dots, s_m . For brevity we denote by y_i, G_i , and b_i the values of $y(s_i)$, $G(s_i)$, and $b(s_i)$ for any i in the set $\{0, 1, \dots, m\}$. We denote by s_{PML} the intensity with probability p_2 of not being exceeded in time T , and we denote by y_{PML} , G_{PML} , and b_{PML} the values $y(s_{PML})$, $d(s_{PML})$, and $\ln G(s_{PML})$. It is assumed here that $y(s)$, $d(s)$, and $\ln G(s)$ are piecewise linear between tabulated values of s . Then

$$G_{PML} = -\ln(p_2)/T \quad (23)$$

Let i denote the index of the discrete values in the hazard and vulnerability functions whose mean exceedance frequency is just lower than G_{PML} and $i-1$ is the index of the point whose mean exceedance frequency is just higher than G_{PML} , i.e., $G_{i-1} \geq G_{PML} > G_i$. Then one can interpolate for s , y , and b corresponding to G_{PML} :

$$\begin{aligned} s_{PML} &= s_{i-1} + \left(\frac{s_i - s_{i-1}}{\ln G_i - \ln G_{i-1}} \right) (\ln G_{PML} - \ln G_{i-1}) \\ y_{PML} &= y_{i-1} + \left(\frac{y_i - y_{i-1}}{s_i - s_{i-1}} \right) (s_{PML} - s_{i-1}) \\ b_{PML} &= b_{i-1} + \left(\frac{b_i - b_{i-1}}{s_i - s_{i-1}} \right) (s_{PML} - s_{i-1}) \end{aligned} \quad \text{for } s_{i-1} \leq s_{PML} < s_i \quad (24)$$

and calculate PML (as a fraction of replacement cost) as

$$PML = \frac{y_{PML}}{\sqrt{\exp(b_{PML}^2)}} \exp(\Phi^{-1}(p_1) \cdot b_{PML}) \quad (25)$$

where Φ denotes the cumulative standard normal distribution evaluated at value of the standard normal variate in parentheses, and where Φ^{-1} denotes its inverse, i.e., the standard normal variate whose nonexceedance probability is shown in the parentheses. Both Φ and Φ^{-1} are standard functions in common analytical software and are also available in probability tables.

Example 6. Consider the as-is building in the previous examples. Calculate the PML where $p_1 = p_2 = 0.90$, and $T = 50$ yr, i.e., the repair cost with 90% nonexceedance probability given shaking with 90% nonexceedance probability in 50 yr.

Solution. Begin by calculating G_{PML} per Equation (23), i.e., $G_{PML} = -\ln(0.90)/50 = 0.002017/\text{yr}$. Values of s , y , and G , can be found in earlier examples. Table 13 draws on Table 3 for s , y , and G for the values whose G bracket G_{PML} . Take for granted the tabulated values of b .

Table 13. Vulnerability and hazard data for Example 6

s	y	G	b
1.2	0.171	0.00242	0.737
1.3	0.178	0.00200	0.717

Now linearly interpolate in the $(s, \ln G)$ space for s_{PML} , according to Equation (24):

$$\begin{aligned} s_{PML} &= 1.2 + \left(\frac{1.3 - 1.2}{\ln 0.002 - \ln 0.00242} \right) \cdot (\ln 0.002107 - \ln 0.002) \\ &= 1.272 \end{aligned}$$

and linearly interpolate in the (s, y) and (s, b) space for y_{PML} and b_{PML} :

$$\begin{aligned} y_{PML} &= 0.171 + \left(\frac{0.178 - 0.171}{1.3 - 1.2} \right) \cdot (1.272 - 1.2) \\ &= 0.176 \\ b_{PML} &= 0.737 + \left(\frac{0.717 - 0.737}{1.3 - 1.2} \right) \cdot (1.272 - 1.2) \\ &= 0.723 \end{aligned}$$

and finally calculate PML:

$$\begin{aligned} PML &= \frac{0.176}{\sqrt{\exp(0.723^2)}} \exp(\Phi^{-1}(0.9) \cdot 0.723) \\ &= 0.342 \end{aligned}$$

That is, the PML is approximately 34% of the replacement cost of the building.

3.6 FACILITY PML FROM A DAMAGE EXCEEDANCE MATRIX AND HAZARD

The hazard function is defined as in Section 3.1, Facility EAL from vulnerability and hazard. The hazard function contains the mean rate (in events per year, denoted by G_j) with which a particular facility will experience various discrete intensity levels, denoted by s_j . The damage exceedance matrix (DEM) is defined as in Section 3.3, Facility EAL from damage exceedance matrix and hazard. The DEM contains probabilities q_{ij} that the uncertain damage factor (denoted by Y) will exceed a particular value z_i , given the occurrence of intensity s_j , where i is a row index and j is a column index. The probable maximum loss, PML , is defined as in Section 3.4. See the same section for definitions of the intensity associated with the

PML (denoted by s_{PML}) and the mean exceedance frequency (events per year) of s_{PML} , denoted by G_{PML} . Let $q(z,s)$ denote the probability that Y will exceed any given value z , given any given intensity s , which is assumed here to vary linearly between tabulated values of q at either constant s or constant z .

The objective is to find PML , i.e., the value of the damage factor z such that the probability of the damage factor exceeding PML is $1 - p_1$, i.e., $q(z, s_{PML}) = (1 - p_1)$. One approach to doing so is to begin by calculating G_{PML} as in Equation (23):

$$G_{PML} = -\ln(p_2)/T \quad (23)$$

This exceedance frequency corresponds to an intensity level s_{PML} , which typically lies between points in the hazard curve. The next step then is to interpolate within the hazard function to calculate s_{PML} . To do so, find j such that $G_{j+1} \leq G_{PML} < G_j$ and then calculate s_{PML} similarly to Equation (24)a:

$$s_{PML} = s_j + \left(\frac{s_{j+1} - s_j}{\ln G_{j+1} - \ln G_j} \right) (\ln G_{PML} - \ln G_j) \quad s_{j-1} \leq s_{PML} < s_j \quad (26)$$

Now interpolate in the DEM to calculate the damage exceedance probabilities at s_{PML} . That is, calculate m damage exceedance probabilities $q_{1,PML}, q_{2,PML}, \dots, q_{m,PML}$:

$$q_{i,PML} = (1-x)q_{i,j} + xq_{i,j+1} \quad i = 1, 2, \dots, m \quad (27)$$

where

$$x = \left(\frac{s_{PML} - s_j}{s_{j+1} - s_j} \right) \quad s_j \leq s_{PML} < s_{j+1} \quad (28)$$

Finally, find i such that $q_{i+1,PML} \leq 1 - p_1 < q_{i,PML}$, and as illustrated in Figure 1, interpolate for PML :

$$PML = z_i + \left(\frac{1 - p_1 - q_{i,PML}}{q_{i+1,PML} - q_{i,PML}} \right) (z_{i+1} - z_i) \quad (29)$$

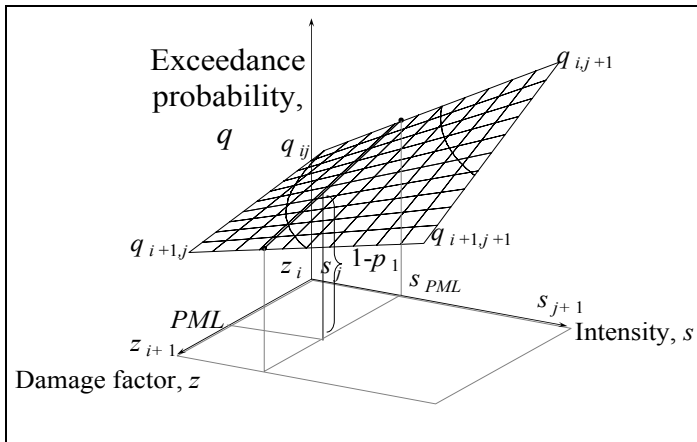


Figure 1. Interpolating DEM between matrix entries to calculate PML

Example 7. Consider the as-is building in the previous examples. Calculate the PML where $p_1 = p_2 = 0.90$, and $T = 50$ yr, i.e., the repair cost with 90% nonexceedance probability given shaking with 90% nonexceedance probability in 50 yr. The DEM is shown in Table 14 and the hazard is shown in Table 15, expressed as mean annual frequency of events with shaking exceeding s .

Table 14. Example 7 DEM

z	Sagm(0.2sec, 5%), g									
	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8	1.9	2
0.001	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
0.002	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
0.003	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
0.005	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
0.007	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
0.010	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
0.020	0.992	0.994	0.996	0.998	0.998	0.999	0.999	0.999	1.000	1.000
0.030	0.968	0.977	0.983	0.987	0.990	0.993	0.994	0.995	0.997	0.997
0.050	0.881	0.903	0.921	0.934	0.945	0.955	0.961	0.966	0.973	0.976
0.070	0.770	0.800	0.827	0.849	0.867	0.884	0.896	0.906	0.919	0.928
0.100	0.605	0.640	0.672	0.700	0.724	0.747	0.766	0.782	0.801	0.816
0.200	0.258	0.281	0.301	0.322	0.340	0.359	0.378	0.393	0.411	0.427
0.300	0.118	0.129	0.139	0.149	0.159	0.168	0.179	0.188	0.197	0.206
0.500	0.032	0.034	0.036	0.039	0.041	0.043	0.046	0.049	0.050	0.053
0.700	0.011	0.011	0.012	0.012	0.013	0.013	0.014	0.015	0.015	0.016
1.000	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003

Table 15. Example 7 Hazard function

	Sagm(0.2sec, 5%), g									
	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8	1.9	2.0
G	0.00294	0.00242	0.00200	0.00167	0.00140	0.00118	0.00100	0.00085	0.00073	0.00062

Solution. Begin by calculating G_{PML} per Equation (23):

$$\begin{aligned} G_{PML} &= -\ln(0.90)/50 \\ &= 0.00211 \end{aligned}$$

Examining Table 15, this value of G is bracketed by 0.00242 events per year with $s \geq 1.2g$, and 0.00200 events per year with $s \geq 1.3g$. Now apply Equation (26) to calculate s_{PML} :

$$\begin{aligned} s_{PML} &= 1.2 + \left(\frac{1.3 - 1.2}{\ln 0.00200 - \ln 0.00242} \right) (\ln 0.00211 - \ln 0.00242) \\ &= 1.2724g \end{aligned}$$

Next calculate x (used to interpolate in the DEM) according to Equation (28)

$$\begin{aligned} x &= \left(\frac{1.2724 - 1.2}{1.3 - 1.2} \right) \\ &= 0.724 \end{aligned}$$

Now interpolate the DEM for $s = 1.2724$, between the columns $s = 1.2$ and 1.3 , using Equation (27). For example, in row 12, corresponding to $z = 0.20g$,

$$\begin{aligned} q_{12,PML} &= 0.724 \cdot 0.301 + (1 - 0.724 \cdot 0.281) \\ &= 0.295 \end{aligned}$$

Results of this calculation are shown in the 4th column of Table 16. Next, search entries in this column to find the rows that bracket $1 - p_1$, i.e., look for i such that $q_{i+1,PML} \leq 1 - p_1 < q_{i,PML}$. Here, $i = 13$, i.e., PML lies between 0.3 and 0.5 times the replacement cost of the facility. Interpolating for PML:

$$\begin{aligned} PML &= 0.3 + \left(\frac{1 - 0.9 - 0.136}{0.035 - 0.136} \right) \cdot (0.7 - 0.3) \\ &= 0.443 \end{aligned}$$

Hence, the PML is approximately 44% of the replacement cost of the facility. In a previous example, PML was calculated as 34% of the replacement cost of the facility. The discrepancy arises in the last calculation because of the linear interpolation between rows of the DEM; the exceedance probability in the earlier example dropped off more quickly, using a lognormal distribution.

Table 16. Interpolating in DEM for Example 7

z	Sagm(0.2sec, 5%), g		
	1.2	1.3	1.272
0.001	1.000	1.000	1.000
0.002	1.000	1.000	1.000
0.003	1.000	1.000	1.000
0.005	1.000	1.000	1.000
0.007	1.000	1.000	1.000
0.010	1.000	1.000	1.000
0.020	0.994	0.996	0.996
0.030	0.977	0.983	0.981
0.050	0.903	0.921	0.916
0.070	0.800	0.827	0.820
0.100	0.640	0.672	0.663
0.200	0.281	0.301	0.295
0.300	0.129	0.139	0.136
0.500	0.034	0.036	0.035
0.700	0.011	0.012	0.012
1.000	0.003	0.003	0.003

3.7 BENEFIT-COST RATIO FOR FACILITY REDESIGN OR RETROFIT

It is assumed here that two design alternatives are under consideration: a base case with initial construction cost denoted by C_0 and expected annualized loss denoted by EAL_0 . There is also a what-if case with initial construction cost denoted by C_r and expected annualized loss denoted by EAL_r . Expected annualized loss figures are calculated elsewhere, perhaps by one of the means discussed above. It is also assumed that the user has selected an after-inflation discount rate denoted by r and has estimated the design life of the facility or of the retrofit denoted by t . The benefit of the redesign or retrofit is calculated here as the present value of the avoided loss,

$$B = (EAL_0 - EAL_r) \frac{(1 - e^{-rt})}{r} \quad (30)$$

Let C denote the construction cost of a retrofit (for an alteration of an existing facility), or the marginal cost of an alternative design (for choosing between two designs for new facilities). The benefit-cost ratio, denoted by BCR , is given by

$$BCR = \frac{B}{C} \quad (31)$$

Example 8. Consider the example retrofit in Section 3.1. Assume a retrofit cost of \$1,500, a risk-free discount rate of 3% and a design life of 30 yr. Calculate BCR.

Solution. As shown in Section 3.1 (before rounding), $EAL_0 = \$412$ and $EAL_r = \$149$. Then by Equation (30), $B = (\$412 - \$149) \times (1 - \exp(-0.03 \times 30))/0.03 = \$5,203$, and by Equation (31), $BCR = \$5,203/\$1500 = 3.5$.

3.8 FACILITY LOSS EXCEEDANCE FREQUENCY FROM HAZARD AND DEM

The loss exceedance frequency (LEF) curve refers to the rate (events per year) at which loss for a given facility exceeds various levels. First consider how to calculate the LEF from a hazard function G and the damage exceedance matrix. Here, as before, G is a vector giving mean events per year with which intensity exceeds various discrete values of intensity s , and the DEM is an $m \times n$ matrix whose entries give the probability of exceeding various levels of damage factor (corresponding to the rows), given a value of the intensity s (corresponding to the columns), for various levels of s . We will calculate the LEF at the same values of the damage factor corresponding to the rows of the DEM. Let

q_{ij} = probability that damage factor z_i is exceeded given the occurrence of intensity s_j

G_j = mean rate (events per year) with which intensity s_j is exceeded

$f(z_i)$ = mean rate (events per year) with which damage factor z_i is exceeded

Let us assume that $\ln(G)$ varies linearly between values of s_j . Given these assumptions, and ignoring a small remainder term for intensities beyond the DEM (i.e., ignoring of $s \geq s_n$),

$$f(z_i) = \sum_{j=2}^n \left(q_{i,j-1} G_{j-1} (1 - \exp(g_j \Delta s_j)) - \frac{\Delta q_{i,j}}{\Delta s_j} G_{j-1} \left(\exp(g_j \Delta s_j) \left(\Delta s_j - \frac{1}{g_j} \right) + \frac{1}{g_j} \right) \right) \quad (32)$$

where

$$\Delta q_{ij} = q_{ij} - q_{ij-1}$$

$$\Delta s_j = s_j - s_{j-1}$$

$$g_j = \frac{\ln(G_j/G_{j-1})}{\Delta s_j} \quad j = 2, 3, \dots, n$$

Example 9. Consider the as-is building in the previous examples. Its hazard function and DEM are shown in Table 17 and Table 18, respectively. Calculate the loss exceedance frequency function at the same values of z as shown in the DEM.

Table 17. Hazard function for Example 9

	Sagm(0.2sec, 5%), g									
	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
G	0.1034	0.0514	0.0296	0.0188	0.0130	0.0096	0.0073	0.0056	0.0045	0.0036

Table 18. DEM for Example 9

z	Sagm(0.2sec, 5%), g									
	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
0.001	0.531	0.841	0.984	0.999	1.000	1.000	1.000	1.000	1.000	1.000
0.002	0.339	0.694	0.947	0.995	0.999	1.000	1.000	1.000	1.000	1.000
0.003	0.241	0.587	0.906	0.987	0.998	1.000	1.000	1.000	1.000	1.000
0.005	0.143	0.443	0.825	0.962	0.991	0.998	0.999	1.000	1.000	1.000
0.007	0.096	0.351	0.753	0.931	0.979	0.993	0.997	0.999	1.000	1.000
0.010	0.059	0.262	0.662	0.878	0.953	0.981	0.992	0.996	0.998	0.999
0.020	0.020	0.130	0.461	0.708	0.838	0.908	0.946	0.967	0.980	0.987
0.030	0.010	0.078	0.344	0.575	0.720	0.814	0.874	0.913	0.940	0.957
0.050	0.003	0.038	0.217	0.396	0.531	0.636	0.714	0.773	0.821	0.855
0.070	0.002	0.022	0.151	0.287	0.399	0.495	0.573	0.635	0.691	0.735
0.100	0.001	0.012	0.097	0.189	0.271	0.347	0.412	0.468	0.521	0.567
0.200	0.000	0.003	0.035	0.067	0.098	0.128	0.156	0.183	0.209	0.234
0.300	0.000	0.001	0.017	0.032	0.045	0.058	0.070	0.082	0.094	0.106
0.500	0.000	0.000	0.006	0.010	0.014	0.017	0.020	0.023	0.025	0.028
0.700	0.000	0.000	0.003	0.005	0.006	0.007	0.007	0.008	0.009	0.010
1.000	0.000	0.000	0.001	0.002	0.002	0.002	0.002	0.002	0.002	0.003

Solution. First calculate $\Delta q_{i,j}$, Δs_j , and g_j for $i = 1, 2, \dots, m$ and $j = 2, 3, \dots, n$. Results are shown in Table 19 and Table 20. For example, (allowing for roundoff error),

$$\begin{aligned} \Delta q_{1,2} &= 0.841 - 0.531 \\ &= 0.310 \\ \Delta s_2 &= 0.2 - 0.1 \\ &= 0.1 \\ g_2 &= \frac{\ln(0.0514/0.1034)}{0.1} \\ &= -6.99 \end{aligned}$$

Table 19. Intermediate results for Example 9: g

	Sagm(0.2sec, 5%)									
	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
g		-6.99	-5.53	-4.50	-3.69	-3.09	-2.75	-2.58	-2.24	-2.24

Table 20. Intermediate results for Example 9: Δq

z	Sagm(0.2sec, 5%)									
	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
0.001		0.311	0.142	0.016	0.001	0.000	0.000	0.000	0.000	0.000
0.002		0.355	0.253	0.048	0.004	0.000	0.000	0.000	0.000	0.000
0.003		0.346	0.319	0.081	0.011	0.002	0.000	0.000	0.000	0.000
0.005		0.300	0.383	0.137	0.029	0.007	0.002	0.000	0.000	0.000
0.007		0.255	0.402	0.177	0.048	0.014	0.005	0.002	0.001	0.000
0.010		0.203	0.400	0.215	0.075	0.028	0.011	0.004	0.002	0.001
0.020		0.109	0.331	0.247	0.130	0.070	0.038	0.021	0.013	0.007
0.030		0.069	0.266	0.231	0.146	0.094	0.060	0.038	0.027	0.017
0.050		0.034	0.179	0.179	0.135	0.105	0.078	0.058	0.048	0.035
0.070		0.020	0.129	0.136	0.113	0.096	0.078	0.063	0.056	0.044
0.100		0.011	0.085	0.093	0.082	0.075	0.065	0.057	0.053	0.045
0.200		0.003	0.032	0.033	0.030	0.030	0.028	0.027	0.026	0.025
0.300		0.001	0.016	0.015	0.013	0.013	0.012	0.012	0.012	0.012
0.500		0.000	0.006	0.004	0.003	0.003	0.003	0.003	0.003	0.003
0.700		0.000	0.003	0.002	0.001	0.001	0.001	0.001	0.001	0.001
1.000		0.000	0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.000

The summand of Equation (32) is shown in Table 28. For example, denoting the summand by x ,

$$x_{12} = 0.531 \cdot 0.1034 \cdot (1 - \exp(-6.99 \cdot 0.1)) - \frac{0.311}{0.1} \cdot 0.1034 \cdot \left(\exp(-6.99 \cdot 0.1) \left(0.1 - \frac{1}{-6.99} \right) + \frac{1}{-6.99} \right)$$

$$= 0.0348$$

Table 21. Intermediate results for Example 9: summand x

z	Sagm(0.2sec, 5%)									
	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
0.001		0.0348	0.0198	0.0106	0.0058	0.0035	0.0023	0.0017	0.0011	0.0009
0.002		0.0258	0.0177	0.0104	0.0058	0.0035	0.0023	0.0017	0.0011	0.0009
0.003		0.0205	0.0160	0.0101	0.0058	0.0035	0.0023	0.0017	0.0011	0.0009
0.005		0.0143	0.0135	0.0095	0.0057	0.0034	0.0023	0.0017	0.0011	0.0009
0.007		0.0109	0.0117	0.0090	0.0055	0.0034	0.0023	0.0016	0.0011	0.0009
0.010		0.0078	0.0097	0.0082	0.0053	0.0033	0.0023	0.0016	0.0011	0.0009
0.020		0.0036	0.0061	0.0062	0.0045	0.0030	0.0021	0.0016	0.0011	0.0009
0.030		0.0021	0.0043	0.0048	0.0037	0.0026	0.0019	0.0015	0.0010	0.0009
0.050		0.0010	0.0026	0.0032	0.0027	0.0020	0.0015	0.0012	0.0009	0.0008
0.070		0.0005	0.0018	0.0023	0.0020	0.0015	0.0012	0.0010	0.0007	0.0006
0.100		0.0003	0.0011	0.0015	0.0013	0.0011	0.0009	0.0007	0.0006	0.0005
0.200		0.0001	0.0004	0.0005	0.0005	0.0004	0.0003	0.0003	0.0002	0.0002
0.300		0.0000	0.0002	0.0003	0.0002	0.0002	0.0001	0.0001	0.0001	0.0001
0.500		0.0000	0.0001	0.0001	0.0001	0.0001	0.0000	0.0000	0.0000	0.0000
0.700		0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
1.000		0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

Finally, the LEF is calculated by summing Table 21 over columns $j = 2, 3, \dots, n$. Results are shown in Table 22 and graphically in Figure 2. For example,

$$f(0.001) = 0.0348 + 0.0198 + 0.0106 + \dots + 0.0009$$

$$= 0.0805$$

which agrees with Table 22 within rounding error.

Table 22. Results of Example 9

z	$f(z)$
0.001	0.0804
0.002	0.0691
0.003	0.0618
0.005	0.0524
0.007	0.0464
0.010	0.0402
0.020	0.0290
0.030	0.0230
0.050	0.0159
0.070	0.0117
0.100	0.0079
0.200	0.0029
0.300	0.0013
0.500	0.0004
0.700	0.0002
1.000	0.0001

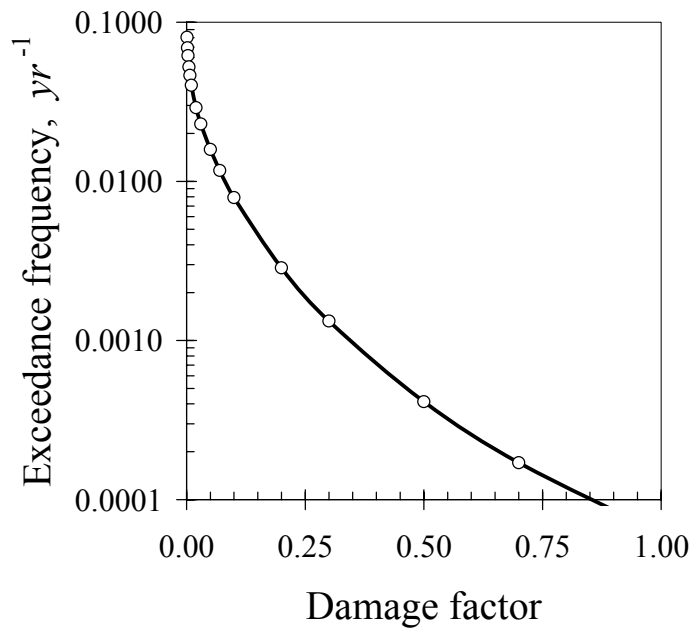


Figure 2. Loss exceedance frequency for Example 9

3.9 LOSS EXCEEDANCE PROBABILITY FROM LEF

It is sometimes desirable to depict an annual probability of exceeding various levels of loss (referred to here as loss exceedance probability, LEP), as opposed to events per year producing loss exceeding various levels (loss exceedance frequency, LEF, discussed previously). Here, LEP is readily calculated from LEF, assuming events occur as a Poisson process. Let

$f(z_i)$ = mean rate (events per year) with which damage factor z_i is exceeded

$p(z_i)$ = probability of one or more events occurring within one year in which damage factor z_i is exceeded.

$$p(z_i) = 1 - \exp(-f(z_i)) \quad (33)$$

Example 10. Consider the as-is building in the previous examples. Its LEF is shown in Table 22. Calculate the loss exceedance probability function at the same values of z as shown in the LEF.

Solution. Applying Equation (33) to the LEF is shown in Table 22 produces the results shown in Table 23 and illustrated in Figure 3. For example, $p(0.001) = 1 - \exp(-0.0804) = 0.0773$, as shown in the table.

Table 23. Results of Example 10

z	$f(z)$	$p(z)$
0.001	0.0804	0.0773
0.002	0.0691	0.0668
0.003	0.0618	0.0599
0.005	0.0524	0.0511
0.007	0.0464	0.0453
0.010	0.0402	0.0394
0.020	0.0290	0.0286
0.030	0.0230	0.0227
0.050	0.0159	0.0158
0.070	0.0117	0.0116
0.100	0.0079	0.0079
0.200	0.0029	0.0029
0.300	0.0013	0.0013
0.500	0.0004	0.0004
0.700	0.0002	0.0002
1.000	0.0001	0.0001

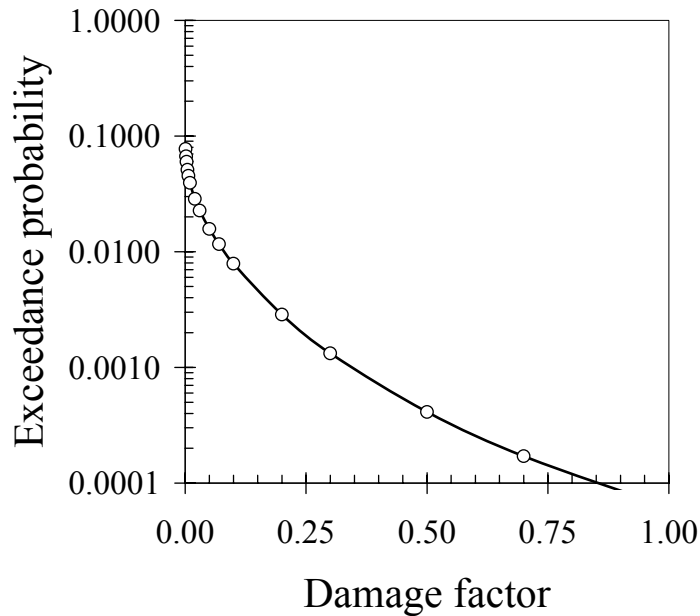


Figure 3. Loss exceedance probability results of Example 10

3.10 FRAGILITY FUNCTION

As used here, a fragility function is a relationship between an input excitation (such as peak horizontal acceleration of the base of the asset) and the probability of an undesirable outcome (such as operational failure of the asset). This section deals provides by reference the math required to create a fragility function from observations of a number of specimens, including both the excitation applied to each and the occurrence or nonoccurrence of the undesirable outcome. See Porter et al. (2007) for the math required for any of the following cases:

- A. Actual excitation, which means you have the approximate value of excitation such as floor acceleration or story drift at which each of several specimens failed.
- B. Bounding excitation, which means you can estimate the maximum value of excitation each of many specimens experienced, and that some of the specimens failed and some did not, etc. B2 and B3 are just alternative ways of calculating fragility functions for type-B data. See Porter et al. (2006) for an explanation of how B2 and B3 differ from B.

- C. Capable excitation, which means you know the excitation to which each specimen was subjected, and that no specimens actually failed.
- E. Expert opinion, which means one or more experts guessed the excitation at which 10% of specimens fail, and at which 50% of specimens fail.
- UA. Updating with type-A data, which means you have an existing fragility function and new evidence where you know the actual excitation at which one or more specimens failed.
- UB. Updating with type-B data, which means you have an existing fragility function and new evidence where you know the maximum excitation to which each of one or more specimens was subjected, and whether or not each specimen failed.

3.11 CALCULATIONS TO BE SPECIFIED AT A LATER DATE

Some important calculations that could be specified here at a later date include the following:

Facility loss exceedance frequency from DPM and hazard. This refers to the rate (events per year) at which loss for a given facility exceeds various levels, given the damage probability matrix and hazard function.

Facility loss exceedance frequency from vulnerability and hazard. This refers to the rate (events per year) at which loss for a given facility exceeds various levels, given the conditional distribution of damage factor as a function of intensity, and the mean hazard function.

Probability of facility operational failure as a function of intensity. This refers to the probability that structural damage, nonstructural damage, loss of utility service, or some combination, will render the facility inoperative, as a function of intensity. An example of such a calculation is shown in Porter et al. (2006).

Facility pro-rata EAL in excess of deductible and below limit. This refers to a fixed fraction (the pro-rata share) of the expected annualized repair cost to a single facility in excess of a threshold fraction of replacement cost (deductible) and less than a higher threshold fraction of replacement cost (limit).

Facility seismic vulnerability by PBEE. This refers to the development of a facility-specific, probabilistic relationship between repair cost (or other loss metric) and shaking intensity, using the principles of second-generation performance-based earthquake engineering. In general, this is 4-stage analytical procedure involving hazard, structural analysis, damage analysis, and loss analysis. The analytical stages can to a large extent be separated and alternative approaches to each one can be implemented and combined, so to document facility seismic vulnerability by PBEE would probably be best done by documenting each stage separately and then showing how they can be combined. The interested reader is referred to Porter and Kiremidjian (2001), Krawinkler (2005), or Comerio (2005) for further details.

4 PORTFOLIO RISK ALGORITHMS

4.1 PORTFOLIO EAL FROM SITE EAL

For present purposes a portfolio refers to one or more assets, where the assets are grouped in non-overlapping groups (i.e., each asset must belong to one and only one group). In insurance applications, groups are most likely to be used to reflect distinct insurance policies, while assets will be used to reflect an insured asset such as a building or the contents of the building. In public-policy applications, a group of assets might refer to the buildings or people in a particular demographic set.

The expected annualized loss to a portfolio of facilities is the simple sum of the *EAL* from the facilities it comprises. Let i denote an index of n facilities in a portfolio, and let EAL_i denote the *EAL* to facility number i calculated by any means such as those shown in Chapter 3. The portfolio EAL is given by:

$$EAL = \sum_{i=1}^n EAL_i \quad (34)$$

4.2 PORTFOLIO LOSS EXCEEDANCE FREQUENCY BY BRUTE FORCE

Data structures required. We refer here to a functional relationship between the expected frequency with which a portfolio of groups of assets produces a catastrophe loss in excess of a particular value, and that value, as a portfolio mean loss exceedance frequency curve. To calculate it by brute force will require calculating, storing, and manipulating, for each of a list of events produced by the event set calculator, the following data:

- The distribution of asset ground-up loss by asset a and event i . The distribution is denoted by LO_{ai} . (By “ground-up” is meant the cost to repair or replace damage to asset a , regardless of any deductibles, limits, pro-rata shares, etc.). Henceforth, a common data structure for loss will include two or three parameter values (mean and standard deviation, and possibly upper bound) and possibly three or more points of the distribution of loss (each point stored with nonexceedance probability and loss value).

- Distribution of LA_{ai} , asset net loss by asset a and event i . (Here, “net loss” means the portion of the ground-up loss borne by the decision-maker whose portfolio is being examined, before the application of group-level limits). The loss has the same data structure as ground-up loss by event a and asset i .
- Distribution of LG_{gi} , net loss by group g and event i , with the same data structure.
- Distribution of LP_i , net portfolio loss by event i , with the same data structure (after summing over all groups g).
- $G0_a(l)$, mean loss exceedance frequency function ground-up loss by asset a (after summing over all events i). The loss exceedance frequency functions described here will be stored in terms of a discrete set of pairs (l, G) , where l denotes a loss value and G a mean rate. The number of such pairs may vary.
- $GA_a(l)$, mean exceedance frequency of net loss by asset a (after summing over all events i). The function can be stored using the same structure as $G0_a(l)$.
- $GG_g(l)$, mean loss exceedance frequency of net loss by group g (after summing over all events i). The function can be stored using the same structure as $G0_a(l)$.
- $GP(l)$, mean loss exceedance frequency of net loss for the portfolio (after summing over all events i).

One way to calculate it is:

$$G_L(l) = \sum_{i=1}^n (1 - F_{Li}(l)) \lambda_{Ei} \quad (35)$$

where $G_L(l)$ denotes the mean loss exceedance frequency evaluated at loss l , the variable i indexes events in an event set containing n events (such as n earthquakes listed by the OpenSHA event-set calculator), and $F_{Li}(l)$ denotes the cumulative distribution function of L_i , the portfolio loss in event i , where F_{Li} is evaluated at l , to be addressed shortly. The variable λ_{Ei} denotes the mean occurrence rate of event i , such as is produced by the OpenSHA event set calculator. The CDF $F_{Li}(l)$ is difficult to calculate in closed form in the presence of potentially correlated asset-level or group-level losses in event i , where because of

deductibles, limits, and other issues losses to the groups may be poorly represented by a parametric distribution such as lognormal, normal, or beta. In the following, we will treat the distribution of loss within a group and in a portfolio as generally as possible without resorting to stochastic simulation (which will be treated in a separate section).

Let L_{gi} denote the uncertain loss to group g in event i , and let L_{ai} denote the uncertain loss to asset a in event i . The mean portfolio loss in event i , denoted by $E[L_i]$, can be calculated as the sum of the expected group-level losses to each group in event i , i.e.,

$$E[L_i] = \sum_{g=1}^m E[L_{g,i}] \quad (36)$$

4.3 SIMULTANEOUS OPERATIONAL FAILURE PROBABILITY

The following discussion refers to fragility functions, which as used here give the probability of an undesirable outcome as a function of input excitation. One example is a component fragility function such as the probability that a given piece of equipment would be rendered inoperative as a function of its base acceleration in an earthquake. Another is a facility-level fragility function, such as the probability that the facility is inoperative as a function of the peak ground acceleration it experiences.

Let i denote an index of facilities in a portfolio of m facilities, and let j denote an index of n scenario events that could affect one or more facilities in the portfolio. Let s_{ij} denote the intensity at site i in scenario event j . Let $P_i(s)$ denote the probability that facility i fails when subjected to intensity s , i.e., the facility-level fragility function for facility i . The nuclear power industry has been developing such fragility functions for decades. The interested reader is referred to Porter et al. (2006) for a recent example of creating facility-level fragility functions from component-level ones. Then $P_i(s_{ij})$ denotes the probability that facility i fails in event j .

Let Q_j denote the failure probability that all n facilities in the portfolio fail in the same scenario event j . One can estimate Q_j as

$$Q_j = P_1(s_{1j}) \times P_2(s_{2j}) \dots \times P_m(s_{mj}) \quad (37)$$

This equation assumes that the failure of the facilities is independent, that is, given the intensity at each site, the failure of one facility has no effect on the failure probability of another, a reasonable assumption where the facilities are not identical and are not constructed by the same contractor at the same time in the same place.

Let R_j denote the rate at which the scenario event j occurs (number of times per year), and let S denote the total mean annual rate (number of times per year) at which all facilities in the portfolio fail in a single scenario event. One can estimate

$$U = R_1 \times Q_1 + R_2 \times Q_2 + \dots R_n \times Q_n \quad (38)$$

or, combining the last two equations,

$$U = \sum_{j=1}^n R_j \left(\prod_{i=1}^m P_i(s_{ij}) \right) \quad (39)$$

Letting V_t the probability that all facilities in the portfolio will simultaneously fail at least once in a single scenario event during a period of t years, one can estimate

$$V_t = 1 - e^{-Ut} \quad (40)$$

where e denotes Euler's number, approximately 2.718. Implicit in this equation is the common simplifying assumption that scenario events are independent. Combining equations (39) and (40) yields

$$V_t = 1 - \exp \left(-t \sum_{j=1}^n R_j \left(\prod_{i=1}^m P_i(s_{ij}) \right) \right) \quad (41)$$

In addition to requiring the fragility functions $P_i(s)$ for each facility i , Equation (41) requires one to describe the hazard to the portfolio via a set of n events whose intensities s_{ix} and s_{iy} are uncorrelated, where $x \neq y$. Porter (2006) presents an example of how to do that for earthquake scenarios, using the ε parameter.

4.4 CALCULATIONS TO BE SPECIFIED AT A LATER DATE

Some important calculations that could be specified here at a later date include the following:

Portfolio-level scenario loss distribution. This refers to the probability distribution of loss to a portfolio of facilities given the intensity each facilities experiences in a single, specified, scenario event.

Portfolio-level single-event loss distribution. This refers to the probability distribution of loss to a portfolio of facilities in a single event, accounting for the rate of events and the intensities they produce at portfolio sites.

Portfolio-level annual loss distribution. This refers to the probability distribution of cumulative loss to a portfolio of facilities in a given year, accounting for the rate of events, the intensities they produce at portfolio sites, and the probability of multiple events occurring during a year that produce losses.

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5 SOFTWARE MODULES TO BE DEVELOPED

This chapter presents details of applications to be developed (Section 5.1) and software objects that could be used in those applications (Section 5.1.2).

5.1 APPLICATION DESIGNS

5.1.1 Single-site BCR calculator

This application has been developed and is available for download from www.risk-agera.org. This application calculates the expected annualized loss (EAL) for a given asset at a given geographic location before and after a retrofit or between as-is and what-if cases. It then calculates benefit as difference between the present value of the EAL under the two cases, and the benefit-cost ratio as the ratio of the calculated benefit to the cost of the retrofit or other what-if alternative. The steps below would be the same whether the intensity measures ground shaking, windspeed, blast overpressure, or possibly other hazards.

1. User starts the application
2. User enters latitude, longitude, identifying description, structure type “as-is,” structure type “what-if,” replacement cost “as-is” (V_0), replacement cost “what-if” (V_r), cost of the retrofit or marginal cost of the design alternative (C), discount rate r , and design life t .
3. User optionally enters vulnerability functions as-is (y) and what-if (y_r), including IMT.
4. User optionally enters site classification (e.g., NEHRP site soil class).
5. User selects hazard calculation method, enters all necessary parameters. Hazard calculation must produce values of same IMT as in vulnerability functions, at same values of IM in the vulnerability functions.
6. User presses “calculate” button.
7. Software looks up site classification if not already specified (e.g., from Wills et al. 2000 soil map).
8. Software performs hazard calculation (or looks up previously calculated hazard).
9. Software calculates EAL as-is and what-if, using math specified in Section 3.1 (pg 25), Eq. (7). In Eq. (7), V_0 is used for V for calculating as-is EAL, and V_r is used for V to calculate what-if EAL.
10. Software calculates benefit and BCR, using math specified in Section 3.7 (pg. 46), Eqs (30) through (31).
11. Software displays results of steps 7-10: site class, hazard, EAL as is, EAL what-if, benefit B, and benefit-cost ratio BCR.

5.1.2 Fragility function calculator

This application has been developed for the Applied Technology Council and is available for research use. Contact Jon Heintz of ATC for access. This stand-alone application calculates fragility functions using any of a variety of methods documented in Porter et al. (2007). The user follows these steps:

1. User starts the application. In color scheme and fonts it looks like other OpenSHA applications. The title is “Fragility Function Calculator.”
2. User sees three vertical panes above and one horizontal pane below.
 - a. **Data echo and output:** the left-hand pane is for data-echo and output.
 - b. **Summary input data:** the middle pane contains (1) Analysis description (in a text box under the label, “Analysis description”) (2) Description of specimens (in a text box under the label “Describe the specimens observed”); (3) Excitation (in a text box under the label, “Describe the excitation imposed”); (4) EDP (in a text box under the label, “Identify the engineering demand parameter”) (5) Damage evidence (in a text box under the label, “Describe how damage was observed”) and (6) DM (in a text box under the label, “Define the damage measure of interest”).
 - c. **Specimen damage data:** the right-hand pane contains tabbed folders, one tab for each method. Methods are listed in Porter et al. (2007), and are named A, B, C, E, and U, but there may be subtypes, e.g., B1, B2, etc.
 - d. **Controls.** The horizontal pane below contains space for future “control panels” drop-down list, a “Compute” button, and a “Clear results” button.
3. User optionally enters data in the middle pane, but this is not necessary.
4. In the tab for Methods A, B, C, E, and U the user enters failure EDP in a spreadsheet-like control either by copy and paste or text entry. Methods E and U have some additional text entry and numerical data fields in the specimen damage data pane along with the spreadsheet control (to be specified later).
5. The user then presses the Compute button, and the calculations shown in Porter et al. (2007) are performed. The results and input data are echoed to the left-hand pane, in the format shown in Figure 4. The user can copy from this pane. The user can perform additional calculations, whose results are appended in this pane.
6. If the user presses a “Plot results” button, the input data and the resulting fragility functions are plotted on an x-y chart, the data appearing as a stepped empirical CDF with data indicated as open circles, and the fragility function as a smooth parametric CDF.
7. If the user presses a “Clear Results” button, the data-echo pane is cleared, as are all stored input data.
8. If the user presses a “Post to database” button, the I/O are all posted to a database that can reside elsewhere on the Internet.

Calculation number: (a counter that starts at 1 and increments until reset when the “clear results” button is pressed)

Analysis description: (the text the user entered in the analysis-description text box)

Specimen description: (the text entered in the specimen-description text box)

Excitation: (the text entered in the excitation-description text box)

EDP: (the text entered in the engineering demand parameter text box)

Damage evidence: (the text entered in the damage-evidence text box)

Damage measure: (the text entered in the damage measure text box)

Analysis method: (A, B, etc., whichever folder was active when the “Compute” button was pressed)

Results

Median capacity: (calculated result x_m)

Logarithmic standard deviation of capacity: (calculated β)

Specimen damage data:
(Echo the data pasted into the specimen-damage-data pane)

Figure 4. Contents of fragility function calculator’s data-echo pane

5.1.3 Portfolio database import tool 1

This section describes an application that imports data from a text file into a database about a portfolio of assets that are exposed to natural disaster risk, for later risk analysis. A portfolio comprises one or more assets located at one or more sites. The assets have attributes such as geographic location, a structure type or vulnerability model, a value exposed to loss. It is also common for the asset data to include fields related to the transfer of financial risk, such as insurance or mortgage information. The typical academic user will probably be creating such a database from scratch; we refer to the tool for the academic user as Portfolio Import Tool 1. The business or civic OpenRisk user may already have compiled a database about these assets for use with commercial or public risk software such as that of RMS, AIR, EQECAT, or HAZUS; we refer to the tool for the business or civic user as Portfolio Import Tool B, which contains one or more built-in templates to map data from the commercial or HAZUS database to that of OpenRisk. It is or will be specified elsewhere.

To return to Portfolio Database Import Tool 1, in overview the user creates a tabular input data file in a standard text format (CSV, XML), starts the application, and either instructs the import tool to import the file to an open-source database such as MySQL, or copies and pastes the data in spreadsheet format to the tool’s GUI. The tool then performs one or more

data checks and prompts the user to interactively correct any data-entry errors. We now turn to the contents of the data file.

As noted before, a portfolio contains one or more assets. Each asset has mandatory data, optional data, and calculated data. Mandatory data must be provided for each asset. Optional data may be provided or not provided, and if not provided a default value is specified below. Calculated data is like optional data, except if not provided by the user it can optionally be calculated from other data sources by the software. Table 24 lists the data that appear in the portfolio database and in the input file. It lists for each field the field name, data type, a description of its contents, an indication of whether the field is required, optional, or calculated, and comments about default values and other requirements.

If the input file is CSV, the first row must contain field names as shown in Table 24, though they need not appear in the same order. The field names can be enclosed in quotes or not. Field names must be separated by commas. Field names that do not appear in Table 24 will be ignored. Lines must end with carriage return and line feed. The subsequent lines must contain the data for the field headers in the same order. If the input file is XML, ... [ISTI to complete].

Table 24. Portfolio Database Import Tool 1 data

Field	Type	Description	Required?	Comment
AssetID	Integer	Asset identifier	Required	Unique identifier
AssetName	String	Name of asset	Optional	
SiteID	Integer	Site identifier	Optional	1+ asset per site, 1+ site per group. Later, hazard may apply to all assets at site.
SiteName	String	Name of site	Optional	
AssetGroupID	Integer	Group identifier	Optional	
AssetGroupName	String	Name of group	Optional	
Lat	Double	Latitude decimal deg north	Required	in ± 90
Lon	Double	Longitude decimal deg east	Required	in ± 180
Value	Float	Expected value exposed to loss. For economic value, best estimate of replacement cost new. For casualties, avg. number of people exposed.	Required	Positive
VulnModel	String	Vulnerability model. Can be structure type, various kinds of furnishings, fixtures, equipment, contents, etc.	Required	Select from available models
Soil	String2	NEHRP site soil classification	Calculated	In {NULL, "A", "AB", "B", "BC", "F"}
Vs30	Float	Mean shearwave velocity in upper 30m of soil	Calculated	NULL or > 0 . If Soil \neq NULL, Vs30 must be within ranges of ICC (2006) Table 1613.5.2.
WindExp	String1	Wind exposure category per ICC (2006) sec 1609.4.3	Calculated	In {NULL, "B", "C", "D"}
Elev	Float	Asset elevation meters above mean sea level [tighter def?]	Calculated	NULL or any float
ValHi	Float	Upper-bound est. (96 th percentile?) of value exposed.	Optional	NULL or ValHi \geq Value
ValLo	Float	Lower-bound estimate (4 th percentile?) of value exposed.	Optional	NULL or $0 <$ ValLo \leq Value

ValYr	yyyy	Year in which value is measured	Optional	
BaseHt	Float	Height above grade (meters) of asset bottom floor	Optional	
LimitLiab	Float	User's limit of liability, in same units as Value	Optional	NULL or ≥ 0
Ded	Float	Loss causing initiation of liability. Same units as Value	Optional	NULL or ≥ 0
Share	Float	Fraction of loss in excess of deductible for which the user is liable	Optional	NULL or in $[0, 1]$

The system use case is as follows.

1. User starts the application. In color scheme and fonts it looks like other OpenSHA applications. The title is "Portfolio database import tool A."
2. User sees two vertical panes above and one horizontal pane below.
 - a. **Output:** the left-hand pane is output in RTF format. Text in the output pane can be selected and copied from, though not pasted to, using standard mouse actions and keystrokes such as Click-drag, Ctrl-A, or right-click-Select-All for select all; or Ctrl-C, Ctrl-Insert, or right-click-Copy for copy.
 - b. **Asset data:** the right-hand pane contains a spreadsheet or database control. Asset data can be copied and pasted into the control, deleted from it by cell, row, or column, or once imported from a text file, echoed and edited there.
 - c. **Controls.** The horizontal pane below contains an "Import" button, an "Export" button, a "Check data" button, a "Clear database" button, and space for future "control panels" drop-down list.
3. User optionally pastes data into the Asset pane.
4. User optionally clicks the Import button. A dialog box opens that asks the user to provide a URL to the import data file, and warns that proceeding will overwrite any data in the asset data pane. Providing a valid URL and clicking the "Open" button in the dialog box causes the data file to be imported to the asset data pane.
5. Data checks are automatically performed. The data checks comprise a review of the rules stated in Table 24. The Output pane reports "Data checked at data/time [date and time]: [X number of] data errors found". The number of problems is reported in Output pane. Problem cells are automatically highlighted somehow (colored red?) in the Asset pane and errors are listed and explained with hypertext in the Output pane. Clicking an error moves the cursor to the problem cell in the Asset pane. Editing a problem cell in the Asset pane and pressing enter or navigating away from it causes the cell to be re-checked, and the highlight is either cleared or if the cell is still a problem the highlight remains, with another explanation appearing on the Output pane. If the problem is cleared, the Output pane reports the correction somehow (e.g., "Problem in cell X,Y corrected by changing value from [old value] to [new value]").

6. The data are nonvolatile. Once imported, they are saved to an Internet-accessible temporary file somewhere (a spreadsheet? database? XML file?), as is the text in the output pane.
7. User optionally clicks the “Check data” button, which causes the checks to be performed again, and new output appended in the Output pane as in Step 5.
8. User optionally clicks the “Export” button, which causes the data to be exported in XML format to an internet-accessible file somewhere, and the contents of the Output pane to be exported to another XML file in the same location. If the data are error-free, a flag in the exported data file indicates that it is ready for use in a portfolio risk analysis.
9. User optionally selects any of the following controls from the “Control panels” drop-down list.

Database import controls

Lookup NEHRP site soil class control. Causes a data update to the Soil and Vs30 fields of each record. If Soil is non-null and within {A, AB, B, ... E}, and Vs30 is non-null and positive, no change is made. Otherwise, pass Lat, Lon, Soil, and Vs30 to the NEHRP site soil class lookup service (Section 5.1.4) and replace Soil and Vs30 with the values returned by it. If practical, show a progress bar labeled “Looking up NEHRP site soil classes.”

Lookup wind exposure control. The control causes a data update of the WindExp field of each record. If WindExp is non-null and within {B, C, D}, no change is made. Otherwise, pass Lat and Lon to the IBC wind exposure category lookup service and replace WindExp with the value returned by the service.

Lookup elevation control. The control causes a data update of the Elev fields of each record. If Elev is non-null, no change is made. Otherwise, pass Lat and Lon to the Elevation lookup service and replace Elev with the value returned by the service.

5.1.4 NEHRP site soil class lookup service

The site soil class lookup service should reside on a server and be Internet accessible. USGS-Pasadena and SCEC have implemented some sort of site-class lookup service, so the service suggested here may be very similar to the one already created for OpenSHA. The only difference may be that it is proposed here that the site class lookup be made to be global, using Wald and Allen’s (2007) global maps of the estimated average shearwave velocity in the upper 30 m of soil, denoted here by Vs30. The maps and their underlying data can be found at <http://earthquake.usgs.gov/vs30>; samples of the maps and data are shown in Figure 5

and Table 25, respectively. Gridpoints are spaced at approximately 1-km increments, and Vs30 is expressed in m/sec.

The service is passed a latitude (decimal degrees N), longitude (decimal degrees E), Site class (in {NULL, A, B, ... E}), and Vs30 (NULL or a positive float). It returns Site class and Vs30, the same type as input but neither is NULL. If the (lat, lon) pair are outside the geographic coverage area of the service, the service returns the input values. Otherwise, if both inputs are NULL, the service returns outputs for site class D per Table 26. If input Soil is non-null and input Vs30 is null or negative, the service returns the input Soil and the value of Vs30 given as the central value for the input Soil listed in Table 26. If both Soil and Vs30 are NULL, the service returns the value of Vs30 spatially interpolated between the nearest 4 gridpoints from USGS Global Vs30 soil map, as explained next, and the corresponding Soil type listed in Table 26.

To spatially interpolate between four gridpoints, first find the values of the latitude and longitude of the nearest 4 gridpoints, along with the Vs30 at each one. Then let the angle between adjacent longitude gridlines be denoted by $\Delta\phi$ and the angle between adjacent latitude gridlines be denoted by $\Delta\lambda$. Let the longitude and latitude of the site be denoted by (ϕ, λ) . Let the longitudes and latitudes of the nearest four gridpoints be denoted by $\{(\phi_1, \lambda_1), (\phi_1 + \Delta\phi, \lambda_1), (\phi_1, \lambda_1 + \Delta\lambda)$ and $(\phi_1 + \Delta\phi, \lambda_1 + \Delta\lambda)\}$, where (ϕ_1, λ_1) denotes the longitude and latitude of the nearest gridpoint with $\phi_1 \leq \phi$ and $\lambda_1 \leq \lambda$, i.e., generally south and west of the site. Transform the $(\phi, \lambda, Vs30)$ coordinate system to an (x, y, z) system where $x = (\phi - \phi_1) / (\Delta\phi)$, $y = (\lambda - \lambda_1) / (\Delta\lambda)$, and $z = Vs30$. Let us denote by z_1, z_2, z_3 , and z_4 the Vs30 values at the (x, y) points (0,0), (1,0), (0,1) and (1,1), respectively. Between any four such gridpoints, interpolate as follows:

$$a_1 = (z_2 - z_1)$$

$$a_2 = (z_3 - z_1)$$

$$a_3 = (z_4 - z_3 - z_2 + z_1)$$

$$a_4 = z_1$$

$$Vs30 = a_1x^2 + a_2y^2 + a_3xy + a_4$$

This is the estimated Vs30 at the building site. Assign the NEHRP site soil classification (A, B, C, etc.) using Table 26 (based on ICC [2006] Table 1613.5.2):

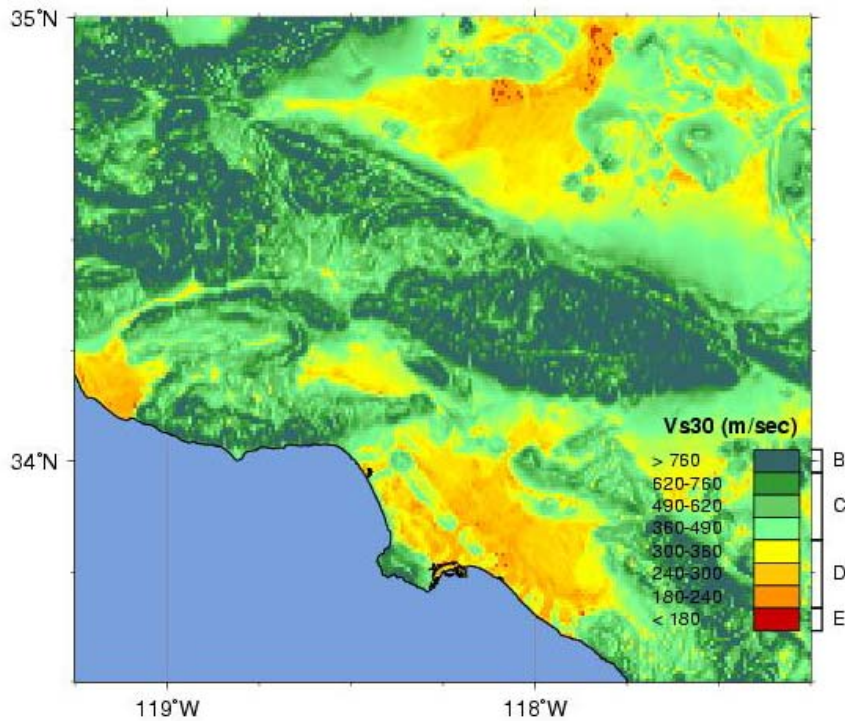


Figure 5. Sample site soil classification map (around Los Angeles, CA)

Table 25. Sample site soil data

Longitude	Latitude	Vs30 (m/s)
-119.246	34.9958	448.332
-119.237	34.9958	472.443
-119.229	34.9958	438.55
-119.221	34.9958	498.86
-119.213	34.9958	514.89
-119.204	34.9958	470.75
-119.196	34.9958	427.82
-119.188	34.9958	434.189
-119.179	34.9958	760

Table 26. Vs30 to site classification lookup

Site classification	Shearwave velocity, Vs30, m/sec	Central value	Stdev
A	Vs30 > 1520 m/sec	2500	580
B	760 < Vs30 ≤ 1520 m/sec	1070	220

C	$360 < V_{s30} \leq 760$ m/sec	520	100
D	$180 \leq V_{s30} \leq 360$ m/sec	250	50
E	$V_{s30} < 180$ m/sec	90	50

Central values for B, C, and D taken from Boore et al. (1997) Table 7. Standard deviations are calculated as if V_{s30} were uniformly distributed between the stated bounds. For calculating the standard deviations and central values of A and E, the upper bound of A and the lower bound of E are taken arbitrarily as 3500 and 0, respectively.

5.1.5 IBC wind exposure category lookup service

This service resides on a server somewhere and returns an IBC wind exposure category (B, C, or D) for a given latitude and longitude. If the latitude and longitude are outside the coverage area of the service, it returns NULL. The service will be detailed later.

5.1.6 Elevation lookup service

This service resides on a server somewhere and returns a ground elevation in meters for a given latitude and longitude. If the latitude and longitude are outside the coverage area of the service, it returns NULL. The service will be detailed later.

5.1.7 Portfolio EAL Calculator 1

The calculator estimates the portfolio expected annualized loss (EAL) for an arbitrary portfolio of assets and an arbitrary peril. It takes as input a portfolio file such as produced by the Portfolio Database Import Tool 1 described in Section 5.1.3 and performs the calculations shown in Section 4.1. It will be relatively slow, as it will calculate EAL on an asset-by-asset basis, generating the hazard for each one on the fly. Nonetheless it is a reasonable place to start.

The user starts the application, and sees a 3-pane interface: two side-by-side panes, and one horizontal pane below. Resembling the BCR application, the left-hand pane is blank but will contain I/O in RTF. The right-hand pane contains tabbed folders labeled “Portfolio and Vulnerability” and a folder labeled “Set Hazard Curve.” The “Set Portfolio and Vulnerability” tab contains only a text box labeled “Enter portfolio URL.” (Maybe additional options later such as demand-surge modeling parameters.) The Set Hazard Curve tab contains groups labeled Set IMR, Set Forecast group, and Set Timespan group, all of which appear in

the BCR application. (The only one from the BCR app that is excluded here is the Set Site Params group, which is not applicable here.) The horizontal pane below contains a drop-down labeled Control Panels, a button labeled “Compute,” another labeled “Clear Results” a checkbox labeled “Show Progress Bar,” and space for the various logos. The system user case is as follows.

1. The user enters the URL to a portfolio filename
2. The user selects options from the Set IMR, Set Forecast, and Set Timespan
3. The user optionally selects “Max site-source distance” from the control panels. The distance must be ≥ 1.0 (km). This limits the sources considered for any asset in the portfolio to those within the set distance.
4. The user optionally selects “Portfolios of interest” from the control panel, which replaces the portfolio file URL with that of any sample portfolios we create, such as LAUSD schools, Palm Springs critical facilities, etc.
5. The user optionally selects “Set Site Params from Web Services” from the control panel drop-down list and sees the same options as in the BCR calculator. The action is the same as in the BCR calculator.
6. The user presses the “Compute” button, which causes the application to loop over the assets in the portfolio input file. For each asset i , the EAL is calculated as in the BCR Application (Section 5.1.1), multiplied by the value of Demand Surge Factor. EAL for the asset is recorded in a portfolio EAL table whose layout is shown in Table 27. Alternatively, the EAL is simply a new field of the portfolio file. The asset EALs are summed and the sum is displayed in the left-hazard pane next to the label “Portfolio EAL =,” after an echo of the input data. In addition, a space-delimited file named EAL.csv is created in some web-accessible directory containing, in each line Lat, Lon, EAL for one asset. There is no header in the file. The EAL file can be used directly in gmtMap.jar; the user is somehow informed of that, taken to the directory via the user’s web browser, and told that the files will be deleted at some pre-established time as with gmtMap.jar.

Table 27. EAL output table, if saved to a separate table. Otherwise EAL is added to Table 24.

Field	Type	Description	From	Comment
ID	Int	Identifier for the asset	Portfolio (Table 24)	Unique in portfolio file
EAL	Double	Expected annualized loss	Equation (7)	

5.1.8 Site loss exceedance frequency calculator

The calculator creates a loss-exceedance frequency curve for a single asset at a single location. It has been created and is available for download from www.risk-agera.org. No system use case has been documented yet, however.

5.1.9 Scenario site loss distribution calculator

To be written.

5.2 APPLICATIONS AND CLASSES TO BE DEVELOPED

Table 28 provides an initial incomplete list of desirable applications to be built. Table 29 provides a summary and incomplete list of object classes to be developed. The table lists the class names, summarizes the purpose of each, suggests a development order or priority, and in some cases points to a later table (Table 30 onward) where the classes' data and methods are thought through in more detail.

Table 28. Applications to be developed

Name	Purpose	Priority	Pg.	Author	Status
SiteBCR	Calculate present value of losses avoided from improving a building and its BCR	H		EM, NG	a
SiteLEF1	Calculate <i>LEF</i> for a building of a given type at a given site using a DEM and hazard curve.	H		EM,NG	a
SiteScenLoss	Calculate loss for a building of a given type at a given site and single scenario event	M	83		
SiteScenLoss2	Calculate loss for a building of a given type at a given site and single scenario event using a ShakeCast map.	L			
SiteEAL	Calculate <i>EAL</i> for a building of a given type at a given site using a hazard curve.	M	84		
SiteLEF2	Calculate <i>LEF</i> for a building of a given type at a given site using OpenSHA event set.	H	85		
SiteFailProb1	Calculate probability of exceeding a given damage state for a building of a given type at a given site and single scenario event using OpenSHA.				
SiteFailProb2	Calculate probability of exceeding a given damage state for a building of a given type at a given site and single scenario event using ShakeCast.				
SiteFailFreq1	Calculate mean annual frequency of exceeding a given damage state for a building of a given type at a given site using OpenSHA hazard curve.				
SiteFailFreq2	Calculate mean annual frequency of exceeding a given damage state for a building of a given type at a given site using NSHMP hazard curve.				
PortfScenLoss	Calculate portfolio scenario loss	L	TBD		
PortfBCR	Calculate BCR for improving a building located at each of a list or grid of geographic coordinates, and map the results	H			
PortfEAL	Calculate portfolio <i>EAL</i> calculator	L	TBD		
PortfLEF	Calculate portfolio loss exceedance frequency	L	TBD		
PortfDS	Calculate portfolio scenario damage state	L	TBD		
	[Various portfolio loss estimates]				

Priority: H = high, M = medium, L = low.

Pg: see this page for details of the module.

Author: person working on code

Status: blank = not begun; 1 = undertaken, not done; a = alpha; b = beta; vX.X = version X.Y released

Table 29. Classes to be developed

Name	Purpose	Priority	Pg.	Author	Status
GenericBuilding	Represent a building of a particular type at a particular site. Not intended to reflect detailed building-specific attributes such as cladding type, setbacks, etc. Flexible enough for earthquake, wind, or flood risk	H	77		
VulnFn	Represent a probabilistic relationship between an intensity measure and a damage factor for a given structure type. Flexible enough to use for earthquake, wind, or flood. Calculates damage factors for a given value of IM.	H	78	EM	1
FragilityFn	Represent the probability of reaching or exceeding a damage state. Calculate probability of exceeding damage state given IM.	H	80	EM	1
DPM	Represent the probability of being in a given damage state, given IM via a damage probability matrix	M			
DEM	Represent the probability of exceeding a given damage factor, given IM via a damage exceedance matrix	H		EM	1
DamageDist	Represent a probabilistic relationship between an intensity measure and discrete damage state for a given structure type. Flexible enough to use for earthquake, wind, or flood. An “intensity measure” can be a scalar or vector measure of the degree of excitation in an event, such as peak ground acceleration, peak gust velocity, peak flood depth, etc. Calculates distribution of damage state for a given value of IM.	H	79	EM	1
HazardCurve	Represent the mean annual frequency of exceeding varying levels of intensity	H	81	EM	1
EqkCatalog	Create artificial catalog of earthquakes affecting given site: given location(s), timescale T, number of series N, generate N equiprobable series of events in spanning the coming T years, including M, location, fault segment, mechanism, etc.,... all parameters needed and in a convenient format for generating shakemaps for each event	H			
AccelSuiteProb	Given a site, T1, and S_a or λ levels, disaggregate M, R, ϵ , and produce sets of a(t) accounting for prescribed probability levels of seismological uncertainties, using Cybershake or recorded accelerogram catalogs.	L			
AccelSuiteScen	Given a site, soil, fault, rupture location, and magnitude, produce sets of a(t) accounting	M			

	for prescribed probability levels of selected seismological uncertainties, using Cybershake or recorded accelerogram catalogs. Indicate reference times so that nearby records can be applied to different points in a structure.				
WillsSoilType	Look up site classification for a latitude and longitude	H		NG	b
FaultDist	Given a site, do the GIS calculation to list fault distances, & indicate potential for surface rupture at site	M			
EventSetIM	Represent the intensity measure distribution at an arbitrary set of sites in an arbitrary number of events	M	81	NG	
StrucTypes	A library of well defined structure types	H	82		
OccTypes	A library of well defined occupancy types	H	82		
Ims	A library of well defined measures of event intensity measures	H	83	EM	1
SiteEAL	Calculate the expected annualized damage factor for a given building	M	84	EM	1
SiteLEF	Calculate the loss exceedance frequency for a given building	L	84		
ContentVuln	Content vulnerability function	M			
DowntimeVuln	Loss of use vulnerability function	M			
BldgPortfolio	Portfolio of general buildings	M			
Various	Address fire, landslide, blast, liquefaction, tornado	L			
Various	Excitation time histories	L			
Various	Generalize from generic building to building component, building occupant	L			
Various	Building-specific features relevant to loss (cladding, geometry, ...)	L			

Priority: H = high, M = medium, L = low.

Pg: see this page for details of the module.

Author: initials of person working on code as of this writing

Status: blank = not begun; 1 = undertaken, not done; a = alpha; b = beta; vX.X = version X.Y released

Table 30. Data and methods of the class “Generic building”

Name	GenericBuilding
Purpose	Represent a building of a particular type at a particular site. Not intended to reflect detailed building-specific attributes such as cladding type, setbacks, etc. Flexible enough for earthquake, wind, or flood risk
Methods	
(Get, set data)	Provide ability to get and set each data item with text arguments and returns. E.g., GetID, SetID, GetName, SetName, etc.
Data	
ID	Building ID. Positive integer
Name	Building name. Text, 250 char
Site	Includes Location (lat, lon, elevation, depth) and a parameter list (e.g., Vs30, WindExp, Slope, HeightAboveChannel)
StrucTypeSys	Must appear in column 0 of the table “Sys” in the object “StructureTypes,” defined below. Text, 10 char
StrucType	Must appear in column 2 of the table “Type” in the object “StructureTypes,” within the set of records of Sys with matching structure type category system. Text, 10 char
RCN	Cost to replace the building new, not including demolition of existing building. Non-negative real
ContentVal	Cost to replace all contents. Non-negative real
Loss-of-useVal	Direct economic loss resulting from loss of use of the building for 1 month. Non-negative real
ValueBasis	Year and ISO 4217 3-character currency code in which RCN is estimated. YYYY<space>CCC
OccTypeSys	Name of occupancy type categorization system; must appear in column 0 of the table “Sys” in the object “OccupancyType,” defined below. Text, 10 char
OccType	Name of occupancy type; must appear in column 1 of the table “Type” in the object “OccupancyType,” within the set of records of OT with matching occupancy type category system. Text, 10 char
Area	Building floor area in m ² including basements. Non-negative real
Year built	Year when oldest or largest part of the building was built. YYYY
Year renovated	Most recent major structural renovation. YYYY. Must be after Year built
Stories	Number of stories, with floors entirely above grade. Non-negative integer.
Basements	Number of basements, counting those who floor is at least partly below grade. Non-negative integer
DaytimeOccs	Average number of occupants at 2:00 PM. Non-negative integer
NighttimeOccs	Average number of occupants at 2:00 AM. Non-negative integer.

Table 31. Data and methods of the class “Vulnerability function”

Name	VulnFn
Purpose	Represent a probabilistic relationship between an intensity measure and a building or content damage factor for a given structure type. Flexible enough to use for earthquake, wind, or flood. Calculate damage factor for a given value of IM.
Methods	
(Get and set data)	(Text arguments and returns)
GetMDF	Calculate mean damage factor (repair cost as a fraction of replacement cost new) given a value of IM. Non-negative real
GetCOVDF	Calculate coefficient of variation of damage factor given a value of IM by interpolating between values in matrix COVDF. Non-negative real
GetDF	Calculate damage factor with probability P of not being exceeded given P and a value of IM. Non-negative real
GetNEP	Calculate probability P of a damage factor DF not being exceeded given DF and IM. Real between 0 and 1
Data	
IMT	Intensity measure type. Must appear in column 0 of table IMT in the object “Ims,” defined below. Text, 10 char
StructureType CategorySystem	Must appear in column 0 of the table “ST” in the object “StructureTypes,” defined below. Text, 10 char
StructureType	Must appear in column 1 of the table “ST” in the object “StructureTypes,” within the set of records of SST with matching structure type category system. Text, 10 char
NIML	Number of discrete intensity measure levels in the lookup tables for both <i>MDF</i> and <i>COVDF</i>
<i>DF</i>	$NIML \times 3$ lookup table of damage factors, where $DF(i,0)$ is intensity measure level, $DF(i,1)$ is mean damage factor at that IML, and $DF(i,2)$ is COV of damage factor at that IML. $DF(i+1,0) > DF(i,0)$; $DF(i+1,1) \geq DF(i,1)$ for all $0 \leq i < NIML$; and all entries are nonnegative real
ADF	Lower bound of DF, used for some distributions, e.g., uniform and beta. Non-negative real
BDF	Upper bound of DF, used for some distributions. Non-negative real $>$ ADF
DistributionType	Type of parametric probability distribution of DF, from list in Appendix. Text, 10 char
Citation	Bibliographic reference for source of the vulnerability function. Text, 250 char

Table 32. Data and methods of class “Fragility model”

Name	DamageDist
Purpose	Represent a probabilistic relationship between an intensity measure and discrete damage state for a given structure type. Flexible enough to use for earthquake, wind, or flood. An “intensity measure” can be a scalar or vector measure of the degree of excitation in an event, such as peak ground acceleration, peak gust velocity, peak flood depth, etc. Calculate distribution of damage state for a given value of IM.
Methods	
(Get, set data)	Including ability to get and set parameters of fragility functions
GetDS	Calculate damage state with probability P of not being exceeded given P and IM. Non-negative integer
GetDSname	Get damage state name given a damage state number. Text, 25 char
GetDSdef	Get damage state definition given a damage state number. Text, 250 char
GetNEP	Calculate probability P of a damage state number DS not being exceeded given DS and IM. Real between 0 and 1
Data	
StructureType CategorySystem	Must appear in column 0 of the table “ST” in the object “StructureTypes,” defined below. Text, 10 char
StructureType	Must appear in column 1 of the table “ST” the object “StructureTypes,” within the set of records of SST with matching structure type category system. Text, 10 char
NDS	Number of damage states
FF	NDS ordered objects the class “Fragility function.” Each must have the same IMT. FF(i) is a lower damage state than FF(i+1) for $i < NDS$. By “lower damage state” is meant that either (A) a building must pass through damage state i before reaching damage state i + 1, or (B) repairing a building from damage state i + 1 necessarily repairs it from damage state i.

Table 33. Data and methods of the class “Fragility function”

Name	FragilityFn
Purpose	Represent the probability of reaching or exceeding a damage state. Calculate probability of exceeding damage state given IM. Note that this class is only used within a DamageDist, so structure type is not needed.
Methods	
(Get, set data)	Provide ability to set all data items with a single method call
GetDSno	Get damage state number (1, 2, ...)
GetP	Calculate the probability that the damage state has been exceeded given IM. Real between 0 and 1
GetName	Get damage state name. Text, 25 char
GetDSdef	Get damage state definition given a damage state number. Text, 250 char
GetNEP	Calculate probability P of a damage state number DS not being exceeded given DS and IM. Real between 0 and 1
Data	
DSno	Damage state number (1, 2, ...)
Name	Damage state name. Text, 25 char
Definition	Damage state definition. Text, 250 char
IMT	Intensity measure type. Must appear in column 0 of table IMT in the object “Ims,” defined below. Text, 10 char
Distribution	Parametric distribution used for the fragility function. Limited to a set of common distributions, e.g., N (normal), LN (lognormal), B (beta), U (uniform). Text, 4 char
m	Central value: mean for N and B, median for LN, not used for U. Positive real
s	Measure of dispersion: standard deviation for N and B, logarithmic standard deviation for LN, not used for U. Positive real
a	Lower bound, used for B and U, not used for N and LN. Nonnegative real
b	Upper bound, used for B and U, not used for N and LN. Nonnegative real, $b > a$
Citation	Bibliographic reference for source of the fragility function. Text, 250 char

Table 34. Data and methods for the class “Hazard curve”

Name	HazardCurve
Purpose	Represent the mean annual frequency of exceeding varying levels of intensity
Methods	
(Get, set data)	Provide ability to enter H with a single function call
GetL	Interpolate within N pairs of (IM,L) data to estimate the mean annual frequency of exceeding a given intensity, where IM represents a scalar measure of intensity and L represents mean annual frequency of exceeding IM. Positive real
GetIM	Interpolate within N pairs of (IM,L) data to estimate the intensity given a mean annual exceedance frequency, where IM represents a scalar measure of intensity and L represents mean annual frequency of exceeding IM. Positive real
Data	
IMT	Intensity measure type. Limited to list in Appendix.
Latitude	Latitude of building footprint centroid, decimal degrees north. Real -90.0 through 90.0
Longitude	Longitude of building footprint centroid, decimal degrees east. Real -180.0 through 180.0
Vs30	Used for seismic hazard only, mean shearwave velocity in upper 30m of soil in m/sec. Non-negative real
Wind Exposure	Used for wind hazard only, wind exposure category per ASCE 7-02. A, B, C, or D
N	Number of intensity levels in the hazard curve. Positive integer
H	$N \times 2$ matrix of (IM, L) pairs, where IM represents a scalar measure of intensity, L represents mean annual frequency of exceeding IM. IM(i) is positive real, L(i) is positive real, IM(i) < IM(i+1), and L(i) > L(i+1)
Citation	Bibliographic reference for source of the hazard curve. Text, 250 char

Table 35. Data and methods for the class “Event set IM”

Name	EventSetIM
Purpose	Represent the intensity measure distribution at an arbitrary set of sites in an arbitrary number of events
Methods	
(Get, set data)	
Data	
ID	Event set ID
Nevents	Number of events considered. Positive integer
Nsites	Number of sites considered. Positive integer
IMT	Intensity measure type. Limited to list in Appendix.
IM	A matrix with (Nevents x Nsites) rows and 4 columns, where IM(i,0) contains Event ID; IM(i,1) contains Site ID; IM(i,2) contains the expected value of IM at this site in this event, and IM(i,3) contains the standard deviation of IM at this site in this event. IM(i,0) is an integer $1 \leq IM(i,0) \leq Nevents$; IM(i,1) is an integer $1 \leq IM(i,1) \leq Nsites$; IM(i,2) is nonnegative real; IM(i,3) is positive real; and no pair (IM(i,0), IM(i,1)) appear more than once.
Citation	Bibliographic reference for source of the IM data. Text, 250 char

Table 36. Data and methods for the class “Structure types”

Name	StrucTypes
Purpose	Library of well defined structure types
Methods	
(Get, set data)	
Data	
NSys	Number of structure type category systems
Sys	NSys x 4 table of structure type category systems, where Sys(i,0) gives index of category system; Sys(i,1) gives short name of category system; Sys(i,2) gives the number of structure types in the category system; and Sys(i,3) gives citation for the category systems. Sys(i,0) is positive integer; Sys(i,1) is text, 50 char; and Sys(i,2) is text, 250 char
Type	N x 4 table of structure types, where ST(i,0) gives a structure type category system index and must appear in Sys(,0); ST(i,1) gives the index of the structure type within the category system; ST(i,2) gives the name of the structure type within that system; and ST(i,3) gives a detailed definition of the structure type. ST(i,0) and ST(i,1) are positive integers without duplicates of the pair; ST(i,2) is text, 10 char; ST(i,3) is text, 250 char

[What about linking with a vulnerability function?]

Table 37. Data and methods for the class “Occupancy types”

Name	OccTypes
Purpose	Represent well defined occupancy types
Methods	
(Get and set data)	
Data	
NSys	Number of occupancy type category systems
Sys	NSys x 4 table of occupancy type category systems, where Sys(i,0) gives index of category system; Sys(i,1) gives short name of category system; Sys(i,2) gives the number of occupancy types in the category system; and Sys(i,3) gives citation for the category systems. Sys(i,0) is positive integer; Sys(i,1) is text, 50 char; and Sys(i,2) is text, 250 char
Type	N x 4 table of occupancy types, where Type(i,0) gives a occupancy type category system index and must appear in Sys(,0); Type(i,1) gives the index of the occupancy type within the category system; Type(i,2) gives the name of the occupancy type within that system; and Type(i,3) gives a detailed definition of the occupancy type. Type(i,0) and Type(i,1) are positive integers without duplicates of the pair; Type(i,2) is text, 10 char; Type(i,3) is text, 250 char

Note that “Occupancy type” and “Structure type” have identical structures and can be inherited form a single base class.

Table 38. Data and methods for the class “Intensity measure type”

Name	Ims
Purpose	Represent well defined intensity measures
Methods	
(Get and set data)	
Data	
NIMTrec	Number of records in table IMT. Nonnegative integer
Ncitation	Number of citations for intensity measure type category systems. Nonnegative integer
IMT	N x 2 table of intensity measure types, where IMT(i,0) gives the name of an intensity measure type and <i>may</i> appear once in Citation(j,0); and IMT(i,1) gives a detailed definition of the intensity measure type. IMT(i,0) is text, 10 char; IMT(i,1) is text, 250 char
Citation	Ncitation x 2 matrix of bibliographic references for intensity measure types, where Citation(i,0) gives the name of the intensity measure type, and Citation(i,1) gives the bibliographic reference for the intensity measure type. Citation(i,0) is text, 10 char; Citation(i,1) is text, 250 char

Table 39. Data and methods for the class “Site scenario loss”

Name	SiteScenarioLoss
Purpose	Calculate the probability distribution of damage factor given a scenario event for a given building and scenario event
Methods	
(Get and set data)	
GetMDF	Calculate mean damage factor (repair cost as a fraction of replacement cost new) given an EventID by applying theorem of total probability to distribution of site IM. Non-negative real
GetCOVDF	Calculate coefficient of variation of damage factor given an EventID by applying theorem of total probability to distribution of site IM. Non-negative real
GetDF	Calculate damage factor with probability P of not being exceeded given P and an event ID. Non-negative real
GetNEP	Calculate probability P of a damage factor DF not being exceeded given DF and EventID. Real between 0 and 1
Data	
EventID	Refers to column 0 of EventSetIM.IM
BuildingID	Refers to GenericBuilding.ID [or column 0 of Portfolio.Building?]

Table 40. Data and methods for the class “Site EAL”

Name	SiteEAL
Purpose	Calculate the expected annualized damage factor for a given building using a hazard curve
Methods	
(Get and set data)	
GetEAL	Calculate expected annualized damage factor (repair cost as a fraction of replacement cost new) given a Building ID, by integrating the site hazard and the building vulnerability function. Math shown in Appendix 1. Non-negative real.
GetEAL	(This method has the same name but different arguments as the previous method.) Calculate expected annualized damage factor (repair cost as a fraction of replacement cost new) given a Building ID, by integrating the site hazard and the damage probability matrix. Math shown in Appendix 2. Non-negative real.
Data	
BuildingID	Refers to GenericBuilding.ID [or column 0 of Portfolio.Building?]

Table 41. Data and methods for the class “SiteLEF1”

Name	SiteLEF
Purpose	Calculate the loss exceedance frequency for a given building given an event set ID
Methods	
(Get and set data)	
calcLEF	Calculate loss exceedance frequency given a Building ID and an Event Set ID, populating matrix LEF.
GetAnLEF	Get loss exceedance frequency for a given damage factor by interpolating in LEF
GetDF	Get a damage factor for a given loss exceedance frequency by interpolating in LEF
Data	
BuildingID	Refers to GenericBuilding.ID [or column 0 of Portfolio.Building?]
EventSetID	Refers to EventSetIM.ID
Orders	Number of orders of magnitude of DF at which to discretize LEF. Positive integer
LEF	Orders x 2 matrix of calculated loss exceedance frequencies, where column 0 contains DF, and column 1 contains loss exceedance frequency. LEF(i,0) is nonnegative real [bounded above by 1?]; LEF(i,1) is nonnegative real

Table 42. Data and methods for the class “SiteLEF2”

Name	SiteLEF
Purpose	Calculate the loss exceedance frequency for a given building given a hazard curve
Methods (Get and set data)	
<i>calcLEF</i>	Calculate loss exceedance frequency given a Building ID and a hazard curve, populating matrix LEF.
<i>GetAnLEF</i>	Get loss exceedance frequency for a given damage factor by interpolating in LEF
<i>GetDF</i>	Get a damage factor for a given loss exceedance frequency by interpolating in LEF
Data	
BuildingID	Refers to GenericBuilding.ID [or column 0 of Portfolio.Building?]
Orders	Number of orders of magnitude of DF at which to discretize LEF. Positive integer
LEF	Orders x 2 matrix of calculated loss exceedance frequencies, where column 0 contains DF, and column 1 contains loss exceedance frequency. LEF(i,0) is nonnegative real [bounded above by 1?]; LEF(i,1) is nonnegative real

6 SEED DATA

6.1 DATA STRUCTURES

It is expected that many contributing OpenRisk developers will be interested only in one analytical component at a time, but their contribution will need to read data from earlier analytical stages and produce results for use in later stages. A common set of interface formats is therefore required, for example, a definition of a data file that contains a vulnerability function, or one that contains a hazard function. Such standard structures are elements of the application programming interface (API). (An API is the source code interface that a computer system or program library provides in order to support requests for services to be made of it by a computer program; <http://en.wikipedia.org/wiki/API>.)

Data can be stored a variety of ways: XML files (self-defining text files), a Microsoft Access database, etc., but one of the simplest and easiest to use is via delimited ASCII text files, in this case using commas to separate fields, double-quotes to contain text fields, and new lines marked by a carriage return followed by a line feed. Each column contains predefined information in an unvarying order and format. Each new line represents a record in the table. This chapter offers two basic file formats and one simple but useful dataset to use in the initial coding of OpenRisk; many more of each are required and will be developed later. Contributors are free to define other data structures, by providing the following:

- A unique data structure name (e.g., “Vulnerability function 2”)
- File naming and location restrictions
- Complete and clear definition of all terms, so that any two readers will reach the same understanding of the format without referring back to the developer.
- Complete and clear definition of file layout, including field and line delimiters

6.2 SAMPLE VULNERABILITY FUNCTIONS

6.2.1 ATC-13 vulnerability functions

ATC-13 vulnerability functions are tabulated below for ease of reading in a report. To express these vulnerability functions in two ASCII text files, the formats proposed in is used:

Table 43. Layout of mean vulnerability function factor ASCII file

Row 1, Title, e.g., "ATC-13 vulnerability functions"
Row 2, Performance metric, e.g., "mean damage factor"
Row 3, Intensity measure, e.g., "IM = MMI"
Row 4, Column header: "No", "Abbreviation", "Description", 6, 7, 8, 9, 10, 11, 12
Rows 5+, vulnerability function contents laid out as labeled in the column header, with fields separated by commas, text fields enclosed in double quotes, and lines terminated with carriage return and line feed characters. Field 1 contains a unique integer identifier for the structure type, Field 2 contains a text abbreviation for the structure type, Field 3 contains a text description of the structure type, and Fields 4 onward contain the mean damage factor (repair cost as a fraction of replacement cost, a floating-point value between 0.0 and 1.0) for the structure type identified in fields 1-3.

Table 44. Layout of vulnerability function coefficient of variation ASCII file

Row 1, Title, e.g., "ATC-13 vulnerability functions"
Row 2, Performance metric: "damage factor coefficient of variation"
Row 3, Intensity measure, e.g., "IM = MMI"
Row 4, Column header: "No", "Abbreviation", "Description", 6, 7, 8, 9, 10, 11, 12
Rows 5+, vulnerability function contents laid out as labeled in the column header, with fields separated by commas, text fields enclosed in double quotes, and lines terminated with carriage return and line feed characters. Field 1 contains a unique integer identifier for the structure type, Field 2 contains a text abbreviation for the structure type, Field 3 contains a text description of the structure type, and Fields 4 onward contain the coefficient of variation of damage factor (the standard deviation of damage factor as a fraction of the mean damage factor, a floating-point value greater than or equal to 1.0) for the structure type identified in fields 1-3.

The following vulnerability functions are taken or derived from ATC-13 (Applied Technology Council 1985). Table 45 contains mean damage factor as a function of MMI for each of 78 ATC-13 facility classes (i.e., structure types). Table 46 contains the coefficient of variation of damage factor as a function of MMI, derived in a three-step process from ATC-13.

First, for each ATC-13 facility class, the implied coefficient of variation of damage factor at each intensity level (indexed by j) is calculated. This COV is denoted here by δ_j , and is calculated as the difference between the ATC-13 experts' weighted-average estimate of the damage factor with 95% and 5% probabilities of nonexceedance (denoted in ATC-13 by "meanh" and "meanl" respectively, and denoted here by h_j and l_j , respectively), divided by the experts' weighted-average estimate of the mean damage factor at intensity j (denoted in ATC-13 by "meanb" and here by y_j) and the number of standard deviations between the 95th and 5th percentiles of the Gaussian distribution, i.e.,

$$\delta_j = \frac{h_j - l_j}{y_j \cdot (\Phi^{-1}(0.95) - \Phi^{-1}(0.05))} \quad (42)$$

Next, for ATC-13 facility class, a regression analysis is performed between δ_j and the MMI indexed by j , denoted here by s_j . It appears from the regression analysis (omitted here) that one can approximate δ_j using the following continuous function:

$$\delta(s_j) = a(s_j)^b \quad (43)$$

Finally, the values of a and b for each facility class are tabulated and $\delta(s_j)$ is evaluated at each value of s_j . The result is shown in Table 46.

Table 45. ATC-13 (1985) seismic vulnerability functions: mean damage factor

No	Abbreviation	Facility class	6	7	8	9	10	11	12
1	W/F/LR	Wood Frame (Low Rise)	0.008	0.015	0.047	0.092	0.198	0.244	0.373
2	M/F/LR	Light Metal (Low Rise)	0.004	0.011	0.021	0.056	0.129	0.223	0.313
3	RC/SW-MRF/LR	Reinforced Concrete Shear Wall (with Moment-Resisting Frame) Low Rise	0.005	0.020	0.047	0.084	0.162	0.266	0.348
4	RC/SW-MRF/MR	Reinforced Concrete Shear Wall (with Moment-Resisting Frame) Medium Rise	0.004	0.023	0.070	0.125	0.233	0.327	0.463
5	RC/SW-MRF/HR	Reinforced Concrete Shear Wall (with Moment-Resisting Frame) High Rise	0.006	0.033	0.069	0.147	0.261	0.452	0.569
6	RC/SW-0/LR	Reinforced Concrete Shear Wall (without Moment-Resisting Frame) Low Rise	0.005	0.028	0.066	0.130	0.236	0.355	0.476
7	RC/SW-0/MR	Reinforced Concrete Shear Wall (without Moment-Resisting Frame) Medium Rise	0.010	0.037	0.088	0.175	0.289	0.395	0.498
8	RC/SW-0/HR	Reinforced Concrete Shear Wall (without Moment-Resisting Frame) High Rise	0.012	0.056	0.118	0.248	0.377	0.540	0.671
9	RM/SW-0/LR	Reinforced Masonry Shear Wall (without Moment-Resisting Frame) Low Rise	0.008	0.029	0.060	0.135	0.232	0.419	0.523
10	RM/SW-0/MR	Reinforced Masonry Shear Wall (without Moment-Resisting Frame) Medium Rise	0.012	0.035	0.099	0.179	0.305	0.461	0.597
11	RM/SW-0/HR	Reinforced Masonry Shear Wall (without Moment-Resisting Frame) High Rise	0.012	0.051	0.133	0.225	0.368	0.550	0.705
12	S/BR/LR	Braced Steel Frame Low Rise	0.006	0.018	0.051	0.101	0.158	0.270	0.388
13	S/BR/MR	Braced Steel Frame Medium Rise	0.008	0.058	0.070	0.119	0.204	0.301	0.418
14	S/BR/HR	Braced Steel Frame High Rise	0.009	0.054	0.102	0.177	0.228	0.378	0.505
15	S/MRF-P/LR	Moment-Resisting Steel Frame (Perimeter Frame) Low Rise	0.007	0.017	0.038	0.072	0.139	0.222	0.314
16	S/MRF-P/MR	Moment-Resisting Steel Frame (Perimeter Frame) Medium Rise	0.007	0.021	0.044	0.089	0.157	0.282	0.364
17	S/MRF-P/HR	Moment-Resisting Steel Frame (Perimeter Frame) High Rise	0.007	0.024	0.062	0.145	0.198	0.367	0.445
18	RC/DMRF-D/LR	Moment-Resisting Ductile Concrete Frame (Distributed Frame) Low Rise	0.004	0.017	0.041	0.092	0.175	0.259	0.419
19	RC/DMRF-D/MR	Moment-Resisting Ductile Concrete Frame (Distributed Frame) Medium Rise	0.013	0.044	0.058	0.108	0.169	0.284	0.371
20	RC/DMRF-D/HR	Moment-Resisting Ductile Concrete Frame (Distributed Frame) High Rise	0.018	0.032	0.069	0.137	0.215	0.318	0.386
21	TU	Tilt-up Low Rise	0.015	0.042	0.106	0.185	0.287	0.450	0.625
23	MH	Mobile Home	0.009	0.030	0.062	0.158	0.287	0.398	0.568
24	SIMPLE-BRIDGE	Conventional Bridge (less than 500-ft spans) Multiple Simple Spans	0.004	0.020	0.088	0.264	0.484	0.816	0.989
25	CONT.-BRIDGE	Conventional Bridge (less than 500-ft spans) Continuous or Monolithic Spans Including Single-Span Bridges	0.001	0.005	0.033	0.099	0.412	0.638	0.894
30	MAJOR-BRIDGE	Major Bridge (greater than 500-ft span)	0.000	0.001	0.002	0.015	0.102	0.285	0.619
31	PIPE-UG	Underground Pipeline	0.000	0.000	0.004	0.007	0.029	0.078	0.192
32	PIPE-AG	At-grade Pipeline	0.000	0.000	0.005	0.011	0.023	0.051	0.141
35	RC-DAM	Concrete Dam	0.000	0.001	0.012	0.034	0.063	0.170	0.298
36	EARTH-DAM	Earthfill and Rockfill Dam	0.002	0.006	0.023	0.058	0.092	0.223	0.396
38	AL-TUNNEL	Tunnel through Alluvium	0.000	0.002	0.008	0.019	0.055	0.120	0.238
39	RK-TUNNEL	Tunnel through Rock	0.000	0.002	0.005	0.018	0.049	0.090	0.164
40	CC-TUNNEL	Cut-and-cover Tunnel	0.000	0.003	0.010	0.028	0.092	0.176	0.292
41	UG-LIQUID-TANK	Underground Liquid Storage Tank	0.001	0.001	0.006	0.025	0.062	0.153	0.278
42	UG-SOLID-TANK	Underground Solid Storage Tank	0.000	0.000	0.005	0.010	0.021	0.035	0.144
43	AG-LIQUID-TANK	On-ground Liquid Storage Tank	0.001	0.005	0.017	0.046	0.156	0.279	0.374

No	Abbreviation	Facility class	6	7	8	9	10	11	12
44	AG-SOLID-TANK	On-ground Solid Storage Tank	0.001	0.008	0.020	0.051	0.171	0.353	0.438
45	EL-LIQUID-TANK	Elevated Liquid Storage Tank	0.003	0.014	0.047	0.104	0.238	0.388	0.586
46	EL-SOLID-TANK	Elevated Solid Storage Tank	0.003	0.014	0.047	0.095	0.200	0.314	0.551
47	RAILROAD	Railroad	0.001	0.009	0.030	0.078	0.125	0.191	0.391
48	HIGHWAY	Highway	0.001	0.006	0.025	0.046	0.096	0.188	0.296
49	RUNWAY	Runway	0.000	0.003	0.036	0.093	0.157	0.197	0.553
50	URM/CHIMNEY	High Industrial Masonry Chimney	0.009	0.061	0.096	0.206	0.388	0.582	0.811
51	RC/CHIMNEY	High Industrial Concrete Chimney	0.004	0.021	0.068	0.151	0.303	0.459	0.641
52	S/CHIMNEY	High Industrial Steel Chimney	0.001	0.008	0.027	0.063	0.164	0.300	0.452
53	CRANE	Crane	0.004	0.014	0.055	0.117	0.253	0.406	0.535
54	CONVEYOR	Conveyor System	0.010	0.021	0.058	0.101	0.157	0.309	0.409
55	STD.-ELEC.-TOWER	Conventional Electric Transmission Line Tower (less than 100 ft high)	0.001	0.006	0.011	0.038	0.091	0.185	0.336
56	MAJOR-ELEC.-TOWER	Major Electric Transmission Line Tower (more than 100 ft high)	0.001	0.007	0.011	0.031	0.080	0.166	0.342
57	BROADCASTING-TOWER	Broadcast Tower	0.005	0.010	0.024	0.049	0.107	0.279	0.491
58	OBSERVATION-TOWER	Observation Tower	0.018	0.027	0.049	0.103	0.150	0.250	0.414
59	OFFSHORE-TOWER	Offshore Tower	0.005	0.007	0.015	0.060	0.137	0.299	0.474
61	CANAL	Canal	0.005	0.011	0.023	0.038	0.097	0.194	0.348
62	EARTH-RET.-STRUCTURE	Earth Retaining Structure over 20 ft High	0.000	0.003	0.006	0.028	0.075	0.172	0.338
63	WATERFRONT-STRUCTURE	Waterfront Structure	0.002	0.017	0.071	0.126	0.251	0.450	0.722
64	RESIDENTIAL-EQUIP.	Residential Equipment	0.005	0.017	0.049	0.125	0.251	0.402	0.531
65	OFFICE-EQUIP.	Office Equipment (Furniture, Computers, etc.)	0.008	0.022	0.054	0.137	0.257	0.431	0.576
66	ELECTRICAL-EQUIP.	Electrical Equipment	0.021	0.037	0.087	0.187	0.318	0.429	0.590
68	MECHANICAL-EQUIP.	Mechanical Equipment	0.005	0.025	0.061	0.127	0.220	0.331	0.485
70	HIGH-TECH-EQUIP.	High Technology and Laboratory Equipment	0.014	0.047	0.130	0.244	0.408	0.591	0.749
72	S/MRF-D/LR	Moment-Resisting Steel Frame (Distributed Frame) Low Rise	0.004	0.014	0.029	0.058	0.108	0.197	0.325
73	S/MRF-D/MR	Moment-Resisting Steel Frame (Distributed Frame) Medium Rise	0.008	0.017	0.043	0.071	0.126	0.196	0.303
74	S/MRF-D/HR	Moment-Resisting Steel Frame (Distributed Frame) High Rise	0.005	0.024	0.049	0.096	0.163	0.242	0.323
75	URM/BRG-WALL/LR	Unreinforced Masonry Bearing Wall Low Rise	0.031	0.101	0.225	0.416	0.646	0.783	0.896
76	URM/BRG-WALL/MR	Unreinforced Masonry Bearing Wall Medium Rise	0.046	0.114	0.288	0.514	0.717	0.830	0.911
78	URM/FR/LR	Unreinforced Masonry with Load-Bearing Frame Low Rise	0.017	0.058	0.141	0.285	0.440	0.602	0.761
79	URM/FR/MR	Unreinforced Masonry with Load-Bearing Frame Medium Rise	0.034	0.082	0.206	0.336	0.473	0.680	0.807
80	URM/FR/HR	Unreinforced Masonry with Load-Bearing Frame High Rise	0.048	0.110	0.235	0.439	0.562	0.689	0.769
81	PCC/LR	Precast Concrete other than Tilt-Up Low Rise	0.011	0.028	0.080	0.232	0.376	0.487	0.600
82	PCC/MR	Precast Concrete other than Tilt-Up Medium Rise	0.011	0.034	0.084	0.272	0.431	0.537	0.687
83	PCC/HR	Precast Concrete other than Tilt-Up High Rise	0.011	0.041	0.101	0.296	0.443	0.546	0.697
84	RM/SW/LR	Reinforced Masonry Shear Wall (with Moment-Resisting Frame) Low Rise	0.010	0.024	0.059	0.119	0.184	0.309	0.513
85	RM/SW/MR	Reinforced Masonry Shear Wall (with Moment-Resisting Frame) Medium Rise	0.014	0.035	0.088	0.152	0.237	0.394	0.578
86	RM/SW/HR	Reinforced Masonry Shear Wall (with Moment-Resisting Frame) High Rise	0.016	0.029	0.071	0.132	0.243	0.401	0.665
87	RC/ND-FR-D/LR	Moment-Resisting Non-Ductile Concrete Frame (Distributed Frame) Low Rise	0.013	0.042	0.121	0.211	0.318	0.475	0.620
88	RC/ND-FR-D/MR	Moment-Resisting Non-Ductile Concrete Frame (Distributed Frame) Medium Rise	0.017	0.051	0.130	0.265	0.357	0.519	0.674
89	RC/ND-FR-D/HR	Moment-Resisting Non-Ductile Concrete Frame (Distributed Frame) High Rise	0.017	0.054	0.133	0.253	0.405	0.553	0.758

No	Abbreviation	Facility class	6	7	8	9	10	11	12
90	VEHICLES	Trains, Trucks, Airplanes, & other Vehicles	0.005	0.010	0.021	0.062	0.120	0.250	0.350
91	LS/LR	Long Span Low Rise	0.003	0.011	0.040	0.090	0.161	0.297	0.457

Table 46. ATC-13 (1985) seismic vulnerability functions: COV of damage factor

No.	Abbreviation	Facility class name	6	7	8	9	10	11	12
1	W/F/LR	Wood Frame (Low Rise)	0.97	0.77	0.62	0.52	0.44	0.38	0.34
2	M/F/LR	Light Metal (Low Rise)	1.07	0.79	0.61	0.48	0.39	0.32	0.27
3	RC/SW-MRF/LR	Reinforced Concrete Shear Wall (with Moment-Resisting Frame) Low Rise	0.95	0.70	0.54	0.43	0.35	0.29	0.24
4	RC/SW-MRF/MR	Reinforced Concrete Shear Wall (with Moment-Resisting Frame) Medium Rise	1.04	0.71	0.51	0.38	0.30	0.23	0.19
5	RC/SW-MRF/HR	Reinforced Concrete Shear Wall (with Moment-Resisting Frame) High Rise	1.02	0.71	0.52	0.39	0.31	0.25	0.20
6	RC/SW-0/LR	Reinforced Concrete Shear Wall (without Moment-Resisting Frame) Low Rise	0.96	0.67	0.50	0.38	0.30	0.24	0.20
7	RC/SW-0/MR	Reinforced Concrete Shear Wall (without Moment-Resisting Frame) Medium Rise	0.77	0.59	0.46	0.37	0.31	0.26	0.22
8	RC/SW-0/HR	Reinforced Concrete Shear Wall (without Moment-Resisting Frame) High Rise	0.74	0.54	0.42	0.33	0.27	0.22	0.18
9	RM/SW-0/LR	Reinforced Masonry Shear Wall (without Moment-Resisting Frame) Low Rise	0.88	0.68	0.54	0.44	0.37	0.31	0.27
10	RM/SW-0/MR	Reinforced Masonry Shear Wall (without Moment-Resisting Frame) Medium Rise	0.80	0.63	0.51	0.42	0.36	0.31	0.27
11	RM/SW-0/HR	Reinforced Masonry Shear Wall (without Moment-Resisting Frame) High Rise	0.92	0.69	0.53	0.42	0.35	0.29	0.24
12	S/BR/LR	Braced Steel Frame Low Rise	1.09	0.79	0.60	0.47	0.38	0.31	0.26
13	S/BR/MR	Braced Steel Frame Medium Rise	0.71	0.57	0.47	0.40	0.35	0.30	0.27
14	S/BR/HR	Braced Steel Frame High Rise	1.04	0.75	0.56	0.44	0.35	0.28	0.24
15	S/MRF-P/LR	Moment-Resisting Steel Frame (Perimeter Frame) Low Rise	0.83	0.63	0.49	0.40	0.33	0.28	0.24
16	S/MRF-P/MR	Moment-Resisting Steel Frame (Perimeter Frame) Medium Rise	0.95	0.71	0.55	0.44	0.36	0.30	0.25
17	S/MRF-P/HR	Moment-Resisting Steel Frame (Perimeter Frame) High Rise	1.31	0.88	0.62	0.46	0.35	0.27	0.22
18	RC/DMRF-D/LR	Moment-Resisting Ductile Concrete Frame (Distributed Frame) Low Rise	1.09	0.74	0.53	0.40	0.30	0.24	0.19
19	RC/DMRF-D/MR	Moment-Resisting Ductile Concrete Frame (Distributed Frame) Medium Rise	0.65	0.52	0.43	0.36	0.31	0.27	0.24
20	RC/DMRF-D/HR	Moment-Resisting Ductile Concrete Frame (Distributed Frame) High Rise	0.68	0.56	0.48	0.41	0.36	0.32	0.29
21	TU	Tilt-up Low Rise	0.73	0.57	0.46	0.38	0.32	0.27	0.24
23	MH	Mobile Home	1.69	1.01	0.65	0.44	0.31	0.22	0.17
24	SIMPLE-BRIDGE	Conventional Bridge (less than 500-ft spans) Multiple Simple Spans	1.28	0.75	0.47	0.31	0.22	0.16	0.12
25	CONT.-BRIDGE	Conventional Bridge (less than 500-ft spans) Continuous or Monolithic Spans Including Single-Span Bridges	1.76	1.01	0.63	0.41	0.28	0.20	0.15
30	MAJOR-BRIDGE	Major Bridge (greater than 500-ft span)	1.74	1.27	0.96	0.76	0.61	0.50	0.42
31	PIPE-UG	Underground Pipeline	4.46	2.57	1.60	1.05	0.72	0.51	0.38
32	PIPE-AG	At-grade Pipeline	1.90	1.40	1.07	0.85	0.69	0.57	0.48
35	RC-DAM	Concrete Dam	1.15	0.89	0.72	0.59	0.50	0.42	0.37
36	EARTH-DAM	Earthfill and Rockfill Dam	0.99	0.80	0.67	0.57	0.50	0.44	0.39
38	AL-TUNNEL	Tunnel through Alluvium	2.07	1.52	1.17	0.93	0.75	0.62	0.53
39	RK-TUNNEL	Tunnel through Rock	1.47	1.07	0.81	0.64	0.51	0.42	0.35
40	CC-TUNNEL	Cut-and-cover Tunnel	2.51	1.77	1.31	1.00	0.79	0.64	0.52
41	UG-LIQUID-TANK	Underground Liquid Storage Tank	1.83	1.33	1.00	0.79	0.63	0.52	0.43
42	UG-SOLID-TANK	Underground Solid Storage Tank	0.76	0.79	0.82	0.84	0.87	0.89	0.91
43	AG-LIQUID-TANK	On-ground Liquid Storage Tank	1.96	1.28	0.88	0.64	0.48	0.37	0.29
44	AG-SOLID-TANK	On-ground Solid Storage Tank	2.27	1.38	0.90	0.61	0.44	0.32	0.24
45	EL-LIQUID-TANK	Elevated Liquid Storage Tank	0.99	0.76	0.61	0.50	0.42	0.35	0.30
46	EL-SOLID-TANK	Elevated Solid Storage Tank	0.81	0.65	0.54	0.46	0.39	0.34	0.30

No.	Abbreviation	Facility class name	6	7	8	9	10	11	12
47	RAILROAD	Railroad	1.69	1.16	0.84	0.63	0.49	0.39	0.32
48	HIGHWAY	Highway	1.72	1.27	0.98	0.77	0.63	0.52	0.44
49	RUNWAY	Runway	0.91	0.70	0.56	0.46	0.38	0.33	0.28
50	URM/CHIMNEY	High Industrial Masonry Chimney	0.88	0.58	0.40	0.29	0.22	0.17	0.13
51	RC/CHIMNEY	High Industrial Concrete Chimney	1.26	0.86	0.62	0.46	0.36	0.28	0.23
52	S/CHIMNEY	High Industrial Steel Chimney	1.55	1.02	0.71	0.52	0.39	0.30	0.24
53	CRANE	Crane	1.35	0.86	0.58	0.41	0.30	0.23	0.18
54	CONVEYOR	Conveyor System	0.59	0.49	0.42	0.36	0.32	0.28	0.25
55	STD.-ELEC.-TOWER	Conventional Electric Transmission Line Tower (less than 100 ft high)	1.78	1.22	0.88	0.66	0.51	0.40	0.33
56	MAJOR-ELEC.-TOWER	Major Electric Transmission Line Tower (more than 100 ft high)	1.77	1.26	0.94	0.73	0.58	0.47	0.39
57	BROADCASTING-TOWER	Broadcast Tower	1.10	0.90	0.75	0.64	0.56	0.49	0.44
58	OBSERVATION-TOWER	Observation Tower	1.00	0.88	0.78	0.71	0.65	0.60	0.56
59	OFFSHORE-TOWER	Offshore Tower	0.91	0.65	0.49	0.38	0.31	0.25	0.21
61	CANAL	Canal	1.83	1.42	1.14	0.94	0.79	0.68	0.59
62	EARTH-RET.-STRUCTURE	Earth Retaining Structure over 20 ft High	1.84	1.36	1.05	0.83	0.68	0.56	0.47
63	WATERFRONT-STRUCTURE	Waterfront Structure	1.49	0.91	0.59	0.41	0.29	0.21	0.16
64	RESIDENTIAL-EQUIP.	Residential Equipment	0.61	0.46	0.37	0.30	0.25	0.21	0.18
65	OFFICE-EQUIP.	Office Equipment (Furniture, Computers, etc.)	0.72	0.54	0.42	0.34	0.28	0.24	0.20
66	ELECTRICAL-EQUIP.	Electrical Equipment	0.95	0.69	0.53	0.41	0.33	0.27	0.23
68	MECHANICAL-EQUIP.	Mechanical Equipment	0.78	0.63	0.52	0.44	0.38	0.33	0.30
70	HIGH-TECH-EQUIP.	High Technology and Laboratory Equipment	0.87	0.64	0.49	0.38	0.31	0.26	0.21
72	S/MRF-D/LR	Moment-Resisting Steel Frame (Distributed Frame) Low Rise	1.37	0.95	0.69	0.52	0.41	0.33	0.26
73	S/MRF-D/MR	Moment-Resisting Steel Frame (Distributed Frame) Medium Rise	1.00	0.76	0.60	0.49	0.41	0.34	0.30
74	S/MRF-D/HR	Moment-Resisting Steel Frame (Distributed Frame) High Rise	1.27	0.93	0.71	0.56	0.45	0.37	0.31
75	URM/BRG-WALL/LR	Unreinforced Masonry Bearing Wall Low Rise	0.95	0.61	0.41	0.29	0.22	0.16	0.13
76	URM/BRG-WALL/MR	Unreinforced Masonry Bearing Wall Medium Rise	0.94	0.58	0.38	0.26	0.19	0.14	0.11
78	URM/FR/LR	Unreinforced Masonry with Load-Bearing Frame Low Rise	1.30	0.89	0.65	0.49	0.38	0.30	0.24
79	URM/FR/MR	Unreinforced Masonry with Load-Bearing Frame Medium Rise	1.02	0.70	0.50	0.38	0.29	0.23	0.18
80	URM/FR/HR	Unreinforced Masonry with Load-Bearing Frame High Rise	0.96	0.66	0.48	0.36	0.28	0.22	0.18
81	PCC/LR	Precast Concrete other than Tilt-Up Low Rise	1.08	0.76	0.56	0.43	0.34	0.27	0.22
82	PCC/MR	Precast Concrete other than Tilt-Up Medium Rise	1.19	0.80	0.57	0.42	0.32	0.25	0.20
83	PCC/HR	Precast Concrete other than Tilt-Up High Rise	1.09	0.76	0.55	0.42	0.33	0.26	0.21
84	RM/SW/LR	Reinforced Masonry Shear Wall (with Moment-Resisting Frame) Low Rise	0.78	0.63	0.52	0.44	0.38	0.33	0.30
85	RM/SW/MR	Reinforced Masonry Shear Wall (with Moment-Resisting Frame) Medium Rise	0.57	0.50	0.44	0.40	0.36	0.34	0.31
86	RM/SW/HR	Reinforced Masonry Shear Wall (with Moment-Resisting Frame) High Rise	0.59	0.52	0.46	0.42	0.38	0.35	0.33
87	RC/ND-FR-D/LR	Moment-Resisting Non-Ductile Concrete Frame (Distributed Frame) Low Rise	0.79	0.58	0.45	0.36	0.29	0.24	0.20
88	RC/ND-FR-D/MR	Moment-Resisting Non-Ductile Concrete Frame (Distributed Frame) Medium Rise	0.77	0.58	0.45	0.36	0.30	0.25	0.21
89	RC/ND-FR-D/HR	Moment-Resisting Non-Ductile Concrete Frame (Distributed Frame) High Rise	0.67	0.52	0.42	0.35	0.29	0.25	0.22
90	VEHICLES	Trains, Trucks, Airplanes, & other Vehicles	1.34	1.05	0.85	0.71	0.60	0.51	0.45
91	LS/LR	Long Span Low Rise	1.81	1.15	0.78	0.55	0.41	0.31	0.24

6.2.2 CUREE-Caltech Woodframe Project vulnerability functions

The following vulnerability functions are developed from repair-cost simulations of several of the index buildings examined in the CUREE-Caltech Woodframe Project (Porter et al. 2002). They are new here however in that they are expressed as functions of 5%-damped, 0.2-sec spectral acceleration response. This was done by plotting the original estimated damage factors from Porter et al. (2002) against the geometric mean $S_a(0.2 \text{ sec}, 5\%)$ of the ground motion pairs used in each simulation, and by then fitting smooth curves to the data. Coefficients of variation are taken from the regression analyses of COV versus mean damage factor, as shown in Porter et al. (2002).

Table 47. Layout of CUREE-Caltech Woodframe Project mean damage factor text file

Row 1, Title: "CUREE-Caltech Woodframe Project vulnerability functions"
Row 2, Performance metric: "mean damage factor"
Row 3, Intensity measure: $IM = S_{agm}(0.2sec, 5\%)$
Row 4, Column header: "No", "Abbreviation", "Index building", 0.1, 0.2, ... 1.0
Rows 5+, vulnerability function contents laid out as labeled in the column header, with fields separated by commas, text fields enclosed in double quotes, and lines terminated with carriage return and line feed characters. Field 1 contains a unique integer identifier for the index building, Field 2 contains a text abbreviation for the index building, Field 3 contains a text description of the index building, and Fields 4 through 13 contain the mean damage factor (repair cost as a fraction of replacement cost, a floating-point value between 0.0 and 1.0) for the index building identified in fields 1-3.

Table 48. Layout of CUREE-Caltech Woodframe Project damage factor COV text file

Row 1, Title: "CUREE-Caltech Woodframe Project vulnerability functions"
Row 2, Performance metric: "damage factor coefficient of variation"
Row 3, Intensity measure: $IM = S_{agm}(0.2sec, 5\%)$
Row 4, Column header: "No", "Abbreviation", "Index building ", 0.1, 0.2, ... 1.0
Rows 5+, vulnerability function contents laid out as labeled in the column header, with fields separated by commas, text fields enclosed in double quotes, and lines terminated with carriage return and line feed characters. Field 1 contains a unique integer identifier for the index building, Field 2 contains a text abbreviation

for the index building, Field 3 contains a text description of the index building, and Fields 4 through 13 contain the coefficient of variation of damage factor (the standard deviation of damage factor as a fraction of the mean damage factor, a floating-point value greater than or equal to 1.0) for the index building identified in fields 1-3.

Table 49. Woodframe Project seismic vulnerability: mean damage vs S_{agm} (0.2 sec, 5%)

No	Abbreviation	Index building	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
2	CWF-102-0205	Woodframe Project small house typical quality S _{agm} (0.2)	0.003	0.011	0.043	0.070	0.090	0.107	0.121	0.133	0.144	0.154
4	CWF-104-0205	Woodframe Project small house retrofit S _{agm} (0.2)	0.000	0.000	0.002	0.020	0.037	0.053	0.068	0.082	0.094	0.106
6	CWF-202-0205	Woodframe Project large house typical quality S _{agm} (0.2)	0.000	0.000	0.000	0.000	0.002	0.009	0.019	0.027	0.034	0.041
8	CWF-204-0205	Woodframe Project large house waist wall S _{agm} (0.2)	0.000	0.000	0.000	0.000	0.002	0.007	0.017	0.026	0.034	0.040
9	CWF-205-0205	Woodframe Project large house immed occ S _{agm} (0.2)	0.000	0.000	0.000	0.000	0.000	0.001	0.002	0.008	0.013	0.017
10	CWF-206-0205	Woodframe Project large house rigid diaphragm S _{agm} (0.2)	0.000	0.000	0.000	0.001	0.003	0.011	0.021	0.029	0.037	0.044
12	CWF-302-0205	Woodframe Project townhouse typical quality S _{agm} (0.2)	0.000	0.000	0.000	0.001	0.004	0.010	0.018	0.026	0.034	0.043
14	CWF-304-0205	Woodframe Project townhouse limited drift S _{agm} (0.2)	0.000	0.000	0.000	0.000	0.000	0.002	0.005	0.009	0.014	0.019

Table 50. Woodframe Project seismic vulnerability: COV of damage vs S_{agm} (0.2 sec, 5%)

No	Abbreviation	Index building	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
2	CWF-102-0205	Woodframe Project small house typical quality S _{agm} (0.2)	2.500	2.500	2.240	1.597	1.330	1.179	1.079	1.008	0.954	0.911
4	CWF-104-0205	Woodframe Project small house retrofit S _{agm} (0.2)	2.500	2.500	2.500	2.500	2.500	1.942	1.629	1.428	1.287	1.184
6	CWF-202-0205	Woodframe Project large house typical quality S _{agm} (0.2)	2.500	2.500	2.500	2.500	1.453	1.000	0.821	0.743	0.696	0.664
8	CWF-204-0205	Woodframe Project large house waist wall S _{agm} (0.2)	2.500	2.500	2.500	2.500	1.531	1.053	0.837	0.751	0.700	0.666
9	CWF-205-0205	Woodframe Project large house immed occ S _{agm} (0.2)	2.500	2.500	2.500	2.500	2.500	2.140	1.472	1.038	0.908	0.837
10	CWF-206-0205	Woodframe Project large house rigid diaphragm S _{agm} (0.2)	2.500	2.500	2.500	1.985	1.365	0.939	0.794	0.725	0.682	0.652
12	CWF-302-0205	Woodframe Project townhouse typical quality S _{agm} (0.2)	2.500	2.500	2.500	2.046	1.212	0.909	0.758	0.667	0.608	0.567
14	CWF-304-0205	Woodframe Project townhouse limited drift S _{agm} (0.2)	2.500	2.500	2.500	2.500	2.500	1.588	1.180	0.955	0.822	0.736

6.2.3 CUREE-Caltech Woodframe Project damage exceedance matrices

The following DEMs are developed from the foregoing seismic vulnerability functions for the CUREE-Caltech Woodframe Project (Porter et al. 2002), using the math shown in Section 3.4, and idealizing the damage factor as lognormally distributed given intensity. The file layout is shown in Table 51.

Table 51. Layout of CUREE-Caltech Woodframe Project DEM ASCII file

Row 1, Title: "CUREE-Caltech Woodframe Project DEM"
Row 2, Index building number, abbreviation, name, e.g., 2, CWF-102-0205, Woodframe Project small house typical quality $S_{agm}(0.2)$
Row 3, Intensity measure: " $S_{agm}(0.2sec, 5\%)$ "
Row 4, Column header: DF, 0.1, 0.2, ... 1.0
Rows 5+, damage exceedance matrix laid out as labeled in the column header, with fields separated by commas.

Table 52. DEM for Woodframe Project small house typ. quality, lognormal CDF given s

DF	$S_{agm}(0.2 \text{ sec}, 5\%)$									
	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
0.001	0.5306	0.8413	0.9837	0.9993	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
0.002	0.3388	0.6941	0.9474	0.9952	0.9995	0.9999	1.0000	1.0000	1.0000	1.0000
0.003	0.2408	0.5868	0.9062	0.9872	0.9979	0.9996	0.9999	1.0000	1.0000	1.0000
0.005	0.1431	0.4429	0.8255	0.9623	0.9908	0.9975	0.9993	0.9998	0.9999	1.0000
0.007	0.0958	0.3510	0.7534	0.9306	0.9786	0.9929	0.9975	0.9990	0.9996	0.9998
0.010	0.0595	0.2624	0.6624	0.8777	0.9528	0.9808	0.9917	0.9962	0.9983	0.9991
0.020	0.0201	0.1296	0.4608	0.7083	0.8379	0.9080	0.9460	0.9671	0.9803	0.9874
0.030	0.0096	0.0783	0.3442	0.5748	0.7204	0.8145	0.8742	0.9125	0.9400	0.9571
0.050	0.0034	0.0376	0.2170	0.3956	0.5310	0.6359	0.7141	0.7726	0.8207	0.8554
0.070	0.0016	0.0218	0.1507	0.2866	0.3991	0.4950	0.5725	0.6354	0.6909	0.7346
0.100	0.0007	0.0115	0.0968	0.1894	0.2713	0.3466	0.4118	0.4684	0.5214	0.5665
0.200	0.0001	0.0029	0.0346	0.0674	0.0975	0.1278	0.1560	0.1825	0.2088	0.2343
0.300	0.0000	0.0011	0.0170	0.0318	0.0448	0.0581	0.0705	0.0824	0.0941	0.1062
0.500	0.0000	0.0003	0.0062	0.0105	0.0138	0.0171	0.0200	0.0228	0.0254	0.0284
0.700	0.0000	0.0001	0.0030	0.0046	0.0056	0.0066	0.0074	0.0082	0.0088	0.0097
1.000	0.0000	0.0000	0.0013	0.0017	0.0019	0.0021	0.0022	0.0024	0.0024	0.0026

6.2.4 HAZUS fatality vulnerability functions

HAZUS (NIBS and FEMA 2003) document a methodology for estimating fatalities (and nonfatal injuries) in ordinary buildings subjected to earthquake excitation. It is practical to calculate from the HAZUS methodology a relationship between 5%-damped elastic spectral acceleration at 0.3 sec or 1.0 sec and the mean fraction of occupants killed. The methodology is documented in Porter (in press). The vulnerability functions are too voluminous to present on paper; they are available in a text file at www.risk-agera.org. They are tabulated for 128 HAZUS structure types (combinations of model building type and code level), 2 seismic domains (western US and central and eastern US), 5 NEHRP site classes, and 16 combinations of magnitude and distance range (relevant to duration, hysteretic energy dissipation, and spectral shape). The table is laid out as shown in the following example:

Table 53. Sample layout of vulnerability-function table

MBTplus	Domain	M	R	Siteclass	IM	$S_S F_a$	SIFv	L
C1Hh	CEUS	5	10	A	Sa10	0.35	0.04	0
C1Hh	CEUS	5	10	A	Sa10	0.71	0.08	8.40E-10

6.3 EARTHQUAKE EVENT SET DESCRIPTION

For a recent project (Porter et al. 2006), the OpenSHA developers created an application to tabulate earthquake shaking intensity at an arbitrarily large number of sites for each of an arbitrarily large number of scenario earthquakes. The output file format is specified in Table 54.

Table 54. Layout of earthquake event set output file

Row 1, Title, e.g., "Event set for Caltech utility analysis performed 1 Jul 2006"
Row 2, Header: "SourceID", "RuptureID", "SiteID", "AttenID", "IMT", "Mean", "Stdev", "Epsilon"
Rows 3+: Intensity estimates laid out as labeled in the column header, with fields separated by commas, text fields enclosed in double quotes, and lines terminated with carriage return and line feed characters. Field 1 contains a unique integer identifier for fault, Field 2 contains an integer identifier for the rupture location on the fault, Field 3 contains an integer identifier for site (a particular latitude and longitude pair), Field 4 contains a

text abbreviation for the seismic attenuation relationship used in this row (e.g., "BJF97"), Field 5 contains a text abbreviation for the intensity measure used in this row (e.g., "PGA"), Fields 6 and 7 contains the expected value and standard deviation of the IMT at this site given the occurrence of an earthquake on this source at this rupture location, and given the value of epsilon specified in Field 8.

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7 DESIGN PRINCIPLES AND DEVELOPMENT GUIDELINES

This section lists programming standards, testing and validation procedures, code library procedures, and documentation procedures.

Programming language. Use Java 2 Standard Edition (J2SE) as the programming language.

Registration of code. Initial registration of code may occur through Sourceforge.net, OpenSHA.org, or www.risk-agera.org, possibly depending on the outcome of a February 2007 AGORA workshop. Sourceforge.net provides a number of standard utilities, while OpenSHA.org provides valuable seismic hazard utilities.

License. Code contributors must accept the OpenRisk license agreement, and agree that any copyright or other language in their code that conflicts with that license agreement may be deleted by the lead developers. (The particular license OpenRisk will use may be decided at the 2007 AGORA workshop.)

Documentation: all methods and objects should have documentation: comments located in the code above the operating code.

Commenting: all code shall be commented so that any reader can understand the code. The author's contact information should be provided within the code so that other readers can contact the author to suggest additional comments, etc.

Version control. Version control should be maintained. Different authors working on the same code should be able to merge their code.

Document design decisions. Every time an object is modified, document the date, summarize the modification including the rationale, and who modified it.

Verification and Validation. Every object shall be required to have an associated test plan at time of submission. The test plan will describe procedures for verification (matches the original design) and validation (fits the intended usage). Requirements for the test plan shall be flexible, and can differentiate objects within the code as either (a) not so complicated or important to call for rigorous junit testing (see junit.org), or (b) complicated or important enough to warrant rigorous junit testing. Meeting the requirements of an accepted Test Plan

will not be required for submission but is required for acceptance of each object (i.e., objects will be identified as “submitted but not accepted pending test completion”). Testing can be performed by those contributing the object, or by others.

Adhere to object-oriented programming principles. For example, do not re-write or modify tested code; use inheritance instead. Use polymorphism. See Complete Reference, Java Tutorial. Don't duplicate code.

Integrate with existing hazard information. Integrate seismic risk elements with OpenSHA, and take advantage of data available from the US National Seismic Hazard Mapping Project, ShakeMap, ShakeCast, PAGER, etc.

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APPENDIX 1 – GLOSSARY

API	Application programming interface
Asset	Humans, animals, property, business operations and other items of value whose reduction in value (loss) is a concern. In general, the economy and built, social and natural environments. Similar terms include exposure, inventory, and portfolio. Note that assets include intangibles such as intellectual property, reputation, etc.
C	Construction cost of a retrofit to an existing facility or added cost associated with an alternative design of a new facility
COV	Coefficient of variation, the ratio of the standard deviation to the mean value of some uncertain quantity.
Damage factor	Repair cost as a fraction of replacement cost new
Damage	Death, collapse, physical injury or other degradation in condition of assets.
EAL	expected annualized loss
F.I.R.E.	Finance, Insurance and Real Estate industries.
Fragility function	A mathematical relationship defining the probability of an undesirable outcome as a function of a measure of input excitation. For example, the probability of a building being red-tagged as a function of the ground shaking measured in terms of MMI. It is common to express fragility functions using a parametric cumulative distribution function (CDF), such as the lognormal CDF.
Group	As used here, a set of assets, not overlapping with other groups.
Hazard	A rubric for the effect of a peril (such as earthquake or flood) at a specific location, or the general pattern of such effects.
Intensity measure	A metric of the effect, or the strength, of a hazard at a specific location. Can be quantitative (e.g., for earthquake, PGA or spectral acceleration response with some particular damping ratio and period) or qualitative (e.g., MMI, MSK, and JMA).
Intensity	The value of the intensity measure

Junit	A unit testing framework for the Java programming language (see www.junit.org and/or http://en.wikipedia.org/wiki/Junit)
JMA	Japan Meteorological Agency (earthquake intensity scale)
Loss	The decrease in asset value resulting from damage. Loss may be direct (the loss-causing damage occurs to the asset in question), or indirect (the loss-causing damage occurs to some other asset, which in turn affects the asset in question).
MMI	Modified Mercalli Intensity scale
MSK	Medvedev Sponheuer Karnik earthquake intensity scale
PBEE	Performance-Based Earthquake Engineering
PGA	Peak Ground Acceleration
PML	probable maximum loss
Portfolio	A set of assets. For example, as used in insurance or finance, a portfolio can represent all the properties insured by a insurer or all the buildings owned by a real estate investor.
Risk analysis	Systematic use of information to identify sources and to estimate risk. Information can include historical data, theoretical analysis, informed opinions, etc.
Risk assessment	Overall process of risk analysis and risk evaluation.
Risk evaluation	Process of comparing the estimated risk against given risk criteria to determine the significance of the risk. Risk evaluation may be used to assist in the decision to accept or to mitigate a risk.
Risk management	The process and acts to reduce risk in an orderly, efficient and desirable manner.
Risk	Any loss that may or may not occur (i.e., is uncertain); can also refer to the probability distribution of the loss.
s	intensity
Seismic hazard	The phenomena or probability of an earthquake-related agent of damage, such as fault rupture, vibratory ground motion (i.e., shaking), inundation (e.g., tsunami, seiche, dam failure), various kinds of

	permanent ground failure (e.g., liquefaction, landsliding), fire, or hazardous materials release..
Seismic risk	Potential or probability of a loss due to the occurrence of earthquakes and associated hazards.
Standard deviation	The square root of the variance of some uncertain quantity
V	Replacement cost of a facility
Variance	The average squared difference between a sample of an uncertain quantity and its mean or average value.
Vulnerability	Generically refers to the probability of damage given the occurrence of a hazard. If damage is defined as the mean damage, the relation with hazard is termed a vulnerability function or curve. In some cases damage and loss are combined, so that vulnerability can be the probability of loss given the hazard. Note also that in the social domain vulnerability has a somewhat different meaning, referring more to the lack of capacity of populations and social systems to cope with disasters.

Vulnerability function

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APPENDIX 2 – HAZUS

Development history. HAZUS has been developed since the early 1990s for national application in the U.S. by FEMA and the National Institute of Building Sciences (NIBS) under the leadership of Philip J. Schneider with, more recently, Barbara J. Schauer, a key manager. The Earthquake model was guided by an Earthquake Committee chaired by Robert V. Whitman (MIT), recently succeeded by William Holmes, and including Mssrs. Borchardt, Brookshire, Eisner, Holmes, Olson, M. O'Rourke, Lagorio and Reitherman. Many people have contributed to HAZUS's development over the years – Charles Kircher was the Technical Project Manager and played a major role in the technical approach, T. Anagnos contributed to injury modeling, S. Chang, H. Cochran and A. Rose to economic modeling, H. Seligson to inventory data, to cite a few. The software development team was led by S. Lawson and M. Bouhafs. Development of HAZUS began in the early 1990s, with its first release in 1997. It went through some birthing pangs (not unusual for software) but is now emerging as a modeling software of choice (see <http://www.hazus.org/>). Kircher et al. (2006) provides a summary of the current capabilities. In 2003, HAZUS-MH (Multi-Hazard) was released with capabilities for flood and hurricane generally similar as those for earthquake.

Intended use and basic capabilities. The initial intent of HAZUS was for emergency and mitigation planning. As such, it is very useful, permitting scenario loss estimates, and an approximation of annualized loss estimates, with a modest hurdle level for entry. Since its inception, other goals have emerged at times – as real-time estimator of losses for emergency response purposes following an event, for example. Users in other countries have adapted it to their regions. The treatment of uncertainty and some other aspects of HAZUS are only approximate however, and the results are not of actuarial quality (which was never the intent). HAZUS executable software is widely distributed free of charge by FEMA to anyone. It is actually an application of ESRI's ARCGIS, so that that proprietary software is required. An investment of perhaps \$5,000 to \$10,000 (current prices) is required, in hardware and the ESRI software.

HAZUS comes with a wealth of inventory and vulnerability data and information, including models (partial in some cases) for shelter needs, injuries, fire following earthquake, hazmat, and an economic model for regional economic impacts (based on the U.S. economy).

The methods are well explained in technical manuals (e.g., NIBS and FEMA 2003), but the software itself is only available in executable version (i.e., no source code), which is an impediment for researchers interested in examining changes in the methodology. For the entry-level user (“Level 1”), obtaining regional loss estimates is relatively straightforward. For a level-2 user, who would wish to substitute more accurate local data or otherwise modify in some even minor way the default data, such modifications require substantial experience. Level-3 users, who can substantially modify the data inputs, are very rare. HAZUS Users Groups (www.hazus.org), provide information on a number of applications, and there are probably hundreds of users, primarily for earthquake although the recently available flood and wind models may increase this significantly.

HAZUS was not initially intended as an earthquake engineering research tool, so its flexibility for research is limited: one can change exposure databases (the inventory of buildings and other assets exposed to loss), soil maps, and some parameters of the fragility and cost data (which relate shaking to loss). The methodology itself however is fixed. For example, the structural analysis employs the capacity spectrum method with single-degree nonlinear oscillator, and cannot be changed to nonlinear dynamic analysis. The damage and loss analyses treat a building as comprising three damageable components (structural, nonstructural drift-sensitive, and nonstructural acceleration-sensitive), with five distinct damage states (plus collapse), and cannot be changed to include more components or different damage states. The treatment of uncertainty is extensive but somewhat incomplete, for example, HAZUS does not produce loss distributions conditioned on a scenario or a shaking intensity.

In summary, after over a decade of development by many members of the US technical community, a free, well-documented software tool is available that permits relatively quick and easy estimates of potential seismic (and now flood and wind) losses, including social and indirect economic impacts, for any community in the U.S. The estimates can easily be modified for various mitigation strategies, and the results can be used for mitigation and emergency response planning. The results are clearly communicated in map and tabular formats. HAZUS is a major contribution to natural hazards reduction.

See Scawthorn et al (2006) for more detail on each of the HAZUS models.