Cracking an Open Safe: More HAZUS Vulnerability Functions in Terms of Structure-Independent Intensity

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In another work, the "open safe" of the HAZUS-MH methodology was cracked to create seismic vulnerability functions that honor all HAZUS-MH methodologies and data, yet that appear in the form of tables of mean casualty rates (indoor deaths and injuries as four fractions of total occupancy) versus a structure-independent intensity measure, in particular, $S_a(0.3\text{ sec}, 5\%)$ or $S_a(1.0\text{ sec}, 5\%)$. In this work, mean repair cost is tabulated against both these intensity measures, for various combinations of model building type, code design level, occupancy class, seismic environment, NEHRP site soil class, magnitude range and distance range. [DOI: 10.1193/1.3153330]

INTRODUCTION

It is common in seismic risk modeling to quantify seismic hazard in terms of the scenario occurrence or probabilistic exceedance frequency of some structure-independent intensity measure such as peak ground acceleration or 5%-damped spectral acceleration at some index period. By combining such hazard information with a relationship between the same intensity measure and loss (a seismic vulnerability function), one can calculate various risk measures: expected annualized loss, loss-exceedance probability, etc. Two of the many uses of such risk information are to inform risk-mitigation decisions such as through cost-benefit analysis; or to inform emergency planning by better understanding the magnitude of future potential losses. In both cases, the stakes can be high, so the vulnerability functions that go into the decision-making need to be authoritative.

Authoritative seismic hazard information is readily available for some areas of the world, e.g., through various online services of the U.S. Geological Survey (USGS). Authoritative seismic vulnerability functions, however, are more problematic to acquire. They generally fall into three categories: empirical (derived from large quantities of historic loss data), expert opinion, and analytical (derived from mathematical models of structural response and construction contracting principles). Examples of empirical models include a study by Whitman et al. (1973) of building damage caused by the 1971 San Fernando earthquake and various post-earthquake investigations presented in Steinbrugge (1982) and Steinbrugge and Algermissen (1990). When the Federal Emergency Management Agency (FEMA) wanted to develop an exhaustive set of vulnerability functions models for California, however, researchers working for the Applied Technology Council (1985) on ATC-13 found that inadequate earthquake experience data existed to

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create vulnerability functions for a wide variety of structure types and resorted instead to the use of expert opinion. They applied a modified version of the Delphi Process to elicit and process that expert opinion in a rigorous, transparent way. Still, expert opinion can be seen to lack authoritativeness.

Analytical methods seem to hold the promise of developing seismic vulnerability functions for buildings that either have not yet experienced earthquakes or for which empirical loss data are not publicly available, without relying on expert opinion. Important pioneering examples of analytical methods include work by Czarnecki (1973) and Kustu et al. (1982). More recently, the present author and others at Caltech and the Pacific Earthquake Engineering Research Center developed and applied second-generation performance-based earthquake engineering (PBEE-2) principles to derive vulnerability functions for several dozen particular woodframe, concrete, and steel buildings (see Porter et al. 2001, 2002a, b, Porter 2003, Krawinkler 2005, or Goulet et al. 2007). For shear diversity of structure types and thorough coverage, however, nothing compares with HAZUS-MH (Kircher et al. 1997, NIBS and FEMA 2003), which provides analytical seismic vulnerability information for most construction common in the United States. Some work has been done to employ the HAZUS-MH methodology for non-U.S. construction (e.g., Robinson et al. 2006) by developing the HAZUS-MH input parameters appropriate to non-U.S. construction.

One important challenge related to employing HAZUS-MH—whether within or outside the United States—is that the vulnerability relationships are derived in part using the capacity spectrum method of structural analysis, which tends to require iteration, followed by extensive calculations of probabilistic damage state and loss. The result is that loss calculations can be extremely time-consuming and loss can be difficult to relate back to a structure-independent intensity measure.

In another work (Porter 2009), it was shown how a seismic vulnerability function can be created that honors all HAZUS-MH methodologies and data but that tabulates mean loss as a function of a structure-independent intensity measure, in particular, geometric-mean-component, site-soil-adjusted $S_a(0.3\text{ sec}, 5\%)$ or $S_a(1.0\text{ sec}, 5\%)$. Here, "honoring all HAZUS-MH methodologies" means that the methodology actually uses the capacity spectrum method of hazard and structural analysis to determine structural response to a scenario earthquake. It accounts for the effects of magnitude, distance, site amplification, seismic regime (western U.S. vs. central and eastern U.S.), hysteretic energy dissipation, and using the HAZUS-MH structural model of an elastic-softening-perfectly plastic single-degree-of-freedom oscillator.

A central challenge addressed in the other work was how to relate the performance point—the structural response expressed in the space of spectral displacement response (S_d), spectral acceleration response (S_a), and effective damping ratio (B_{eff})—back to a structure-independent intensity measure such as $S_a(0.3\text{ sec}, 5\%)$ and $S_a(1.0\text{ sec}, 5\%)$. The key distinction between the coordinates of the performance point and these latter intensity measures is that the period and damping ratio associated with the performance point vary. When the structure is excited beyond yield, stronger motion tends both to lengthen the period and to increase the effective damping ratio. So although the coordinates of the performance point look like an intensity measure—they are after all measured in terms of spectral acceleration and spectral displacement response—one does not know in advance which period or damping ratio to use to measure seismic intensity. They are structure-dependent. By contrast, one does not need to know anything about the building to estimate $S_a(0.3\ \text{sec}, 5\%)$ and $S_a(1.0\ \text{sec}, 5\%)$, e.g., from a ground-motion prediction equation. They are structure-independent.

The trick was to start with a value of S_d, calculate S_a of the performance point from the HAZUS-MH pushover curve, calculate effective damping, and back out the associated values of $S_a(0.3\ \text{sec}, 5\%)$ or $S_a(1.0\ \text{sec}, 5\%)$ of the site-soil-adjusted idealized response spectrum. Then, working forward from the performance point, one can calculate probabilistic damage state and mean loss and finally relate the two end products: loss vs. structure-independent intensity measure.

One repeats the process at various values of S_d: backward to $S_a(0.3\ \text{sec}, 5\%)$ and $S_a(1.0\ \text{sec}, 5\%)$, and forward to S_a of the performance point and to mean loss at each (S_d, S_a) pair. By tabulating the structure-independent intensity measure and corresponding mean loss, one arrives at a convenient seismic vulnerability function that can be used with more-readily-accessible seismic hazard information to estimate risk at any arbitrary location and HAZUS-MH model building type. The prior work includes sample calculations and a pointer to a free, online database of seismic vulnerability functions for mean indoor fatality rate (www.risk-agora.org; free registration is required).

The present work adds the calculation of repair cost as a fraction of replacement cost, again as a function of site-soil-adjusted $S_a(0.3\ \text{sec}, 5\%)$ and $S_a(1.0\ \text{sec}, 5\%)$ for a combination of any of 5 NEHRP site soil classes, 4 magnitude ranges, 4 distance ranges, two seismic regions (western U.S. or central and eastern U.S.), 36 model building types, 4 code eras, and 33 occupancy classes. The resulting seismic vulnerability functions can be combined with hazard information expressed in terms of $S_a(0.3\ \text{sec}, 5\%)$ or $S_a(1.0\ \text{sec}, 5\%)$ to estimate risk, consistently with but in some cases more conveniently than, HAZUS-MH.

METHODOLOGY

The hazard and structural analysis portions of the calculation are the same as in Porter (2009), and are not reiterated here. Only the damage and loss analyses differ. Let us begin then with the assumption that one has selected NEHRP site soil class, magnitude, distance, seismic region, model building type, and code era. One has also selected a performance point—the point in (S_d, S_a) space where the building capacity curve intersects the demand spectrum—and calculated as shown in the prior work the associated structure—independent intensity measures of site-soil-adjusted $S_a(0.3\ \text{sec}, 5\%)$ and $S_a(1.0\ \text{sec}, 5\%)$. Let us denote the performance point here by (x, y). In the following calculations, it will be necessary also to select an occupancy class: there are 33 of them in HAZUS-MH; the first few are shown in Table 1.

Table 1. Sample of HAZUS-MH occupancy classes (from NIBS and FEMA 2003 Table 15.2)

Number	Label	Occupancy Class
		Residential
1	RES1	Single Family Dwelling
2	RES2	Mobile Home
3–8	RES3a-f	Multi Family Dwelling
9	RES4	Temporary Lodging
10	RES5	Institutional Dormitory
11	RES6	Nursing Home
		Commercial
12	COM1	Retail Trade
13	COM2	Wholesale Trade

The calculation of structural damage is now briefly recapped, followed by a relatively simple extension for nonstructural damage. For damage-analysis purposes, HAZUS-MH treats a building as comprising three components: structural, nonstructural drift-sensitive, and nonstructural acceleration-sensitive. Let us denote by D_1 the uncertain damage state of the structural component. It can take on any of 6 values: undamaged (denoted here by $D_1=0$), slight, moderate, or extensive damage (denoted here by $D_1=1$, 2, and 3, respectively), complete but not collapsed ($D_1=4$), and collapsed ($D_1=5$). Let us denote by D_2 and D_3 the uncertain damage state of the nonstructural drift-sensitive and nonstructural acceleration-sensitive building components. Each can take on any of 5 values: $D=0$, 1, 2, 3, and 4, which here denote undamaged, slight, moderate, extensive, and complete damage, respectively. For purposes of calculating repair cost, "collapse" is the same as "complete but not collapsed."

STRUCTURAL DAMAGE

The probability that structural damage reaches or exceeds damage states 1 through 4 are approximated in HAZUS-MH as a cumulative lognormal distribution with median value denoted here by θ and logarithmic standard deviation denoted here by β. Each damage state has its own (θ, β) pair, indicated here by a subscript of the damage-state number. The probability of each structural damage state is given as a function solely of x:

$$
\begin{aligned}
P[D_1 = d | S_d = x] &= 1 - \Phi\left(\frac{\ln(x/\theta_1)}{\beta_1}\right) \quad d = 0 \\
&= \Phi\left(\frac{\ln(x/\theta_d)}{\beta_d}\right) - \Phi\left(\frac{\ln(x/\theta_{d+1})}{\beta_{d+1}}\right) \quad 1 \leqslant d \leqslant 3 \\
&= (1 - P_c)\Phi\left(\frac{\ln(x/\theta_4)}{\beta_4}\right) \quad d = 4 \\
&= P_c\Phi\left(\frac{\ln(x/\theta_4)}{\beta_4}\right) \quad d = 5
\end{aligned}
\tag{1}
$$

where $P[D_1{=}d|S_d{=}x]$ denotes the probability of structural damage state d given that S_d takes on some particular value x; Φ denotes the cumulative standard normal distribution whose parameters are denoted by θ_i and β_i. These are tabulated in NIBS and FEMA (2003) Tables 5.9a-d. The fraction of building area collapsed among buildings with complete damage is denoted by P_c, which is recorded in the text of NIBS and FEMA (2003) Section 5.3.1.

Note that the β values shown here are appropriate to probabilistic risk analysis, as opposed to scenario loss calculation or post-earthquake loss estimation where the shaking intensity at the building site is deterministic or observed, e.g., by strong-motion instruments.

NONSTRUCTURAL DAMAGE

Calculations similar to Equation 1 are performed to determine the probabilistic damage state of the nonstructural components: drift-sensitive components use $S_d{=}x$ at the performance point as input, as shown in Equation 2, while acceleration-sensitive components use $S_a{=}y$ as input, as shown in Equation 3. We calculate:

$$
\begin{aligned}
P[D_2 = d | S_d = x] &= 1 - \Phi\left(\frac{\ln(x/\theta_1)}{\beta_1}\right) \quad d = 0 \\
&= \Phi\left(\frac{\ln(x/\theta_d)}{\beta_d}\right) - \Phi\left(\frac{\ln(x/\theta_{d+1})}{\beta_{d+1}}\right) \quad 1 \leqslant d \leqslant 3 \\
&= \Phi\left(\frac{\ln(x/\theta_4)}{\beta_4}\right) \quad d = 4
\end{aligned}
\tag{2}
$$

Table 2. Sample fragility curve parameters for high-code design and nonstructural drift-sensitive building components (NIBS and FEMA 2003 Table 15.11a)

Building type	Median spectral displacement (inches) and logarithmic standard deviation (beta)							
	Slight		Moderate		Extensive		Complete	
	Median	Beta	Median	Beta	Median	Beta	Median	Beta
W1	0.50	0.85	1.01	0.88	3.15	0.88	6.30	0.94
W2	0.86	0.87	1.73	0.89	5.40	0.96	10.80	0.94
S1L	0.86	0.81	1.73	0.85	5.40	0.77	10.80	0.77
S1M	2.16	0.71	4.32	0.72	13.50	0.72	27.00	0.80

$$\begin{aligned} P[D_3 = d | S_a = y] &= 1 - \Phi\left(\frac{\ln(y/\theta_1)}{\beta_1}\right) \quad d = 0 \\ &= \Phi\left(\frac{\ln(y/\theta_d)}{\beta_d}\right) - \Phi\left(\frac{\ln(y/\theta_{d+1})}{\beta_{d+1}}\right) \quad 1 \leqslant d \leqslant 3 \\ &= \Phi\left(\frac{\ln(y/\theta_4)}{\beta_4}\right) \quad d = 4 \end{aligned} \tag{3}$$

The Equation 2 parameters θ_d and β_d for use with nonstructural drift-sensitive damage D_2 are shown in Table 5.11a-d of NIBS and FEMA (2003), a sample of which is shown in Table 2. The parameters for use in Equation 3, for nonstructural acceleration-sensitive damage D_3, are contained in Table 5.13a-d of NIBS and FEMA (2003), a sample of which is shown in Table 3. In Equation 3, we use y to denote a particular value of S_a, to indicate that it is the y-component of the performance point. Again, the β values shown here are appropriate to probabilistic risk calculation, as opposed to situations where the ground motion is deterministic, such as in post-earthquake loss estimation where the ground motion at the building site is observed via strong-motion instrumentation.

Table 3. Sample fragility curve parameters for high-code design and nonstructural acceleration-sensitive building components (NIBS and FEMA 2003 Table 15.11a)

Building type	Median spectral acceleration (g) and logarithmic standard deviation (beta)							
	Slight		Moderate		Extensive		Complete	
	Median	Beta	Median	Beta	Median	Beta	Median	Beta
W1	0.30	0.73	0.60	0.68	1.20	0.68	2.40	0.68
W2	0.30	0.70	0.60	0.67	1.20	0.67	2.40	0.68
S1L	0.30	0.67	0.60	0.67	1.20	0.68	2.40	0.67
S1M	0.30	0.67	0.60	0.68	1.20	0.67	2.40	0.67

Table 4. Sample HAZUS repair cost ratios or structural damage, extracted from NIBS and FEMA (2003) Table 15.2. Figures expressed as percent of building replacement cost

			Structural Damage State			
No.	Label	Occupancy Class	Slight	Moderate	Extensive	Complete
1	RES1	Single Family Dwelling	0.5	2.3	11.7	23.4
2	RES2	Mobile Home	0.4	2.4	7.3	24.4
3–8	RES3a-f	Multi Family Dwelling	0.3	1.4	6.9	13.8
9	RES4	Temporary Lodging	0.2	1.4	6.8	13.6

MEAN REPAIR COSTS

For purposes of estimating repair costs, let L denote mean repair cost as a fraction of replacement cost new. It is calculated as

$$L = \sum_{d=1}^{5} P[D_1 = d|S_d = x]L_{1d} + \sum_{d=1}^{4} P[D_2 = d|S_d = x]L_{2d} + \sum_{d=1}^{4} P[D_3 = d|S_a = y]L_{3d} \quad (4)$$

where x and y denote S_d and S_a at the performance point, respectively, D_1, D_2, and D_3 are as defined above, L_{1d} denotes the structural repair cost ratio for structural damage state d (i.e., the structural repair cost as a fraction of the total building replacement cost new), L_{2d} denotes the nonstructural drift-sensitive repair cost ratio for nonstructural drift-sensitive-component damage state d, and L_{3d} denotes the nonstructural acceleration-sensitive repair cost ratio for nonstructural drift-sensitive-component damage state d. The probabilities $P[D_1=d|S_d=x]$, $P[D_2=d|S_d=x]$, and $P[D_3=d|S_a=y]$ are as calculated in Equations 1–3, respectively. The values of L_{1d}, L_{2d} and L_{3d} are contained in NIBS and FEMA (2003) Tables 15.2, 15.4, and 15.3, respectively. The first few lines of NIBS and FEMA (2003) Table 15.2 are recapped in Table 4; the other tables have a similar appearance. Note that the structural repair cost ratio for the collapsed damage state is the same as that of complete structural damage, so in Equation 4, one takes L_{15} as being the same as L_{14}. Also note that L_{1d}, L_{2d}, and L_{3d} depend on occupancy class, as illustrated in Table 4.

SAMPLE CALCULATIONS

For the sample calculation, consider a high-code wood-frame, single-family dwelling (model building type W1 and occupancy class RES1) on a western U.S. site, with NEHRP site class D. Consider S_d=1.0 in. In Porter (2009), it was shown that

S_a(0.41 sec, 32% damping)=0.59 g; this is the period and effective damping ratio at the performance point

S_1F_v=0.88 g; this is the corresponding 5%-damped, 1-sec spectral acceleration response on NEHRP site class D

S_SF_a=1.48 g; this is the corresponding 5%-damped, 0.3-sec spectral acceleration response on NEHRP site class D

Table 5. Structural damage state probabilities

P_1	P_2	P_3	P_4	P_5
0.50	0.28	0.024	0.0044	0.0001

The probabilistic structural damage state is as tabulated in Table 5. For purposes of hysteretic energy dissipation and the shape of the idealized response spectrum, the sample calculation considered the case of M=7 and R=20 km, but these are not used to calculate S_d.

The fragility function parameters θ and β applied in Equations 2 and 3 for W1 high code are shown in Table 2 and Table 3, respectively. Applying Equation 2,

$$
\begin{aligned}
P[D_2 = d | S_d = 1.0] &= 1 - \Phi\left(\frac{\ln(1.0/0.5)}{0.85}\right) = 0.21 \quad d = 0 \\
&= \Phi\left(\frac{\ln(1.0/0.5)}{0.85}\right) - \Phi\left(\frac{\ln(1.0/1.01)}{0.88}\right) = 0.30 \quad d = 1 \\
&= \Phi\left(\frac{\ln(1.0/1.01)}{0.88}\right) - \Phi\left(\frac{\ln(1.0/3.15)}{0.88}\right) = 0.40 \quad d = 2 \\
&= \Phi\left(\frac{\ln(1.0/3.15)}{0.88}\right) - \Phi\left(\frac{\ln(1.0/6.30)}{0.94}\right) = 0.07 \quad d = 3 \\
&= \Phi\left(\frac{\ln(1.0/6.30)}{0.94}\right) = 0.02 \quad d = 4
\end{aligned}
$$

Applying Equation 3,

$$
\begin{aligned}
P[D_3 = d | S_a = 0.59] &= 1 - \Phi\left(\frac{\ln(0.59/0.3)}{0.73}\right) = 0.18 \quad d = 0 \\
&= \Phi\left(\frac{\ln(0.59/0.3)}{0.73}\right) - \Phi\left(\frac{\ln(0.59/0.6)}{0.68}\right) = 0.33 \quad d = 1 \\
&= \Phi\left(\frac{\ln(0.59/0.6)}{0.68}\right) - \Phi\left(\frac{\ln(0.59/1.2)}{0.68}\right) = 0.34 \quad d = 2 \\
&= \Phi\left(\frac{\ln(0.59/1.2)}{0.68}\right) - \Phi\left(\frac{\ln(0.59/2.4)}{0.68}\right) = 0.13 \quad d = 3 \\
&= \Phi\left(\frac{\ln(0.59/2.4)}{0.68}\right) = 0.02 \quad d = 4
\end{aligned}
$$

Table 6. Sample calculation of Equation 4

	Structural			Nonstructural drift-sens			Nonstructural accel-sens		
D	P	L_{1d}	$P \cdot L_{1d}$	P	L_{1d}	$P \cdot L_{1d}$	P	L_{1d}	$P \cdot L_{1d}$
1	0.50	0.005	0.0025	0.30	0.010	0.0030	0.33	0.005	0.0017
2	0.28	0.023	0.0064	0.40	0.050	0.0200	0.34	0.027	0.0093
3	0.02	0.117	0.0028	0.07	0.250	0.0178	0.13	0.080	0.0105
4	0.00	0.234	0.0010	0.02	0.500	0.0126	0.02	0.266	0.0054
5	0.00	0.234	0.0000						
		Σ=	0.0128		Σ=	0.0533		Σ=	0.0268
								L=	0.0930

Table 6 illustrates Equation 4 with L_{1d}, L_{2d}, and L_{3d} from Table 4. In the table, "P" is short for the probability terms in the equation. The calculations are performed with more significant figures than shown here, although of course this is not to imply that the results are accurate to more than one or two significant figures.

Figure 1 shows the seismic vulnerability function for this and other values of S_d. The dot shows the point calculated here.

RESULTS

The foregoing calculations were performed for every combination of 36 model building types (e.g., woodframe less than 5,000 sf), 4 code eras (pre-, low-, moderate-, and high-code), 33 occupancy classes (e.g., single family dwelling), five NEHRP site soil classes (A, B, C, D, and E), four earthquake magnitudes (5, 6, 7, and 8), four site

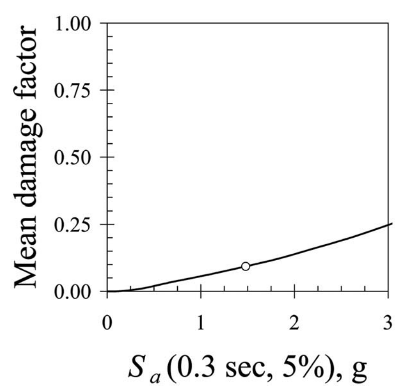

Figure 1. Sample seismic vulnerability function: W1, high code, RES1 occupancy, soil=D, M=7, etc. Dot shows results of foregoing sample calculations.

Table 7. Sample layout of vulnerability-function table

MBTplus	Occ	Domain	M	R	Siteclass	IM	S_SF_a	S_1F_v	L
W1h	RES1	WUS	7	20	D	Sa03	1.48	0.88	0.09
W1h	RES1	WUS	7	20	D	Sa03	1.83	1.10	0.12

distances (10, 20, 40, and 80 km), and two seismic regions (western U.S. or central and eastern U.S.). The results are available in text files at www.risk-agora.org, in the format illustrated in Table 7.

In the table, "MBTplus" refers to the HAZUS-MH model building type (e.g., W1, meaning woodframe $<$5,000 sf) plus a character to indicate code era (e.g., h, meaning high code). "Occ" refers to the HAZUS occupancy class (e.g., RES1, meaning single family dwelling). "Domain" refers to whether the function is appropriate for western U.S. ("WUS") or central and eastern U.S. ("CEUS"). M refers to the approximate magnitude and R to the approximate distance (used here only for spectral shape and duration effects). "Siteclass" refers to the NEHRP site soil classification (A, B, C, D, or E). "IM" indicates whether the performance point corresponds to a point on the constant-acceleration portion of the index spectrum ("Sa03") or on the constant-velocity portion of the index spectrum ("Sa10"), and therefore which of the two subsequent intensity measures is probably more appropriate to use to estimate loss: "S_SF_a," which refers to the 5%-damped, site-soil-adjusted spectral acceleration response at 0.3 sec period, or "S_1F_v," the 5%-damped, site-soil-adjusted spectral acceleration response at 1.0 sec period, both expressed in units of gravity. Finally, "L" refers to mean damage factor, which here gives the expected value of repair cost as a fraction of replacement cost new. In the table, L is not rounded to a fixed number of decimal places simply because it was not convenient to do so, but of course the reader should not infer accuracy beyond perhaps one or two significant figures.

CONCLUSIONS

It can be useful for estimating seismic risk to have seismic vulnerability functions expressed in terms of a table of mean loss versus a structure-independent intensity measure such as $S_a(1.0\text{ sec}, 5\%)$. To estimate seismic risk at the societal level requires a suite of seismic vulnerability functions representing the building types that contribute most significantly to risk, either because they are numerous, vulnerable, or both. HAZUS-MH offers perhaps the most extensive set of analytically derived vulnerability relationships currently available, though in a form that can be hard to use outside HAZUS-MH, because losses are not tabulated against a structure-independent intensity measure, and to calculate them as is done within HAZUS-MH tends to involve an iterative solution of the capacity-spectrum-method performance point.

A large number of such seismic vulnerability functions are created here that honor all HAZUS-MH methodologies and data, covering all common U.S. building types, while avoiding an iterative solution to find the performance point. The resulting vulnerability functions are limited to construction that is common in the United States, and for use in probabilistic loss calculation. However, the methodology is generally applicable to other structure types and to cases of deterministic shaking, if one can derive or acquire the necessary parameter values.

The seismic vulnerability functions produced here are available for free download from www.risk-agora.org. While the vulnerability functions are voluminous, they should be readily usable with any database software. Following the mathematical procedures presented here, one should be able to produce similar seismic vulnerability functions for other structure types or using parameter values that differ from the ones offered by the HAZUS-MH developers.

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