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Developing Screening Criteria for Buildings at Risk from Seismic Damage

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Abstract

This brief report proposes an engineering basis to support USACE's existing seismic safety action classification (SSAC) system. The SSAC characterizes the importance of a detailed seismic evaluation for a USACE building. SSAC is an ordinal scale in which a building is assigned a value of 1, 2, 3, 4, or 5, with 1 being worst and 5 best, and in which buildings with a classification of 1 or 2 are deemed to be high priorities for detailed seismic evaluation. It distinguishes between non-essential and essential facilities, the difference being that USACE specifies that some facilities (essential facilities) should remain functional after a large earthquake, and others (non-essential) need to be life safe. We propose that SSAC for non-essential facilities be taken as the FEMA P-154 S value, rounded to the nearest integer, plus 1.0. for essential facilities, we propose that SSAC be based on the probability that a facility will be rendered nonfunctional given the mapped, risk-targeted maximum-considered earthquake (MCE_R) shaking (from ASCE 7) at the facility site. In particular, the it equates the SSAC with the negative log-10 probability of nonfunctionality, rounded to the nearest integer, plus 1.0, very similar to our proposed use of the FEMA P-154 S score for non-essential facilities. We use Hazus-MH extensive damage states for the three components that Hazus uses to idealize a building as proxies for nonfunctionality. USACE will prioritize detailed seismic evaluation or mitigation efforts on buildings with lower SSAC values. We consider two options for prioritizing within a group of buildings with the same SSAC value: (1) prioritize on the basis of average annualized fatalities, or (2) average annualized economic loss. We provide algorithms for calculating both annualized loss values.

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1. Introduction

1.1 Project background

USACE's seismic safety action classification (SSAC) characterizes the importance of a detailed seismic evaluation for a USACE building. SSAC is an ordinal scale in which a building is assigned a value of 1, 2, 3, 4, or 5, with 1 being worst and 5 best, and in which buildings with a classification of 1 or 2 are deemed to be high priorities for detailed seismic evaluation. A building with SSAC = 3 is not without risk, but where remediation is less likely to be cost effective in terms of protecting life. How to provide an engineering basis for assigning SSAC? This report documents a system for assigning an SSAC. It distinguishes between non-essential and essential facilities, the difference being that USACE specifies that some facilities (essential facilities) should remain functional after a large earthquake, and others (non-essential) need to be life safe.

USACE will prioritize detailed seismic evaluation or mitigation efforts on buildings with lower SSAC values. How to assign relative priorities to any two facilities with the same SSAC? We consider two options: (1) prioritize on the basis of average annualized fatalities, or (2) average annualized economic loss. That is, if one SSAC = 1 building will have a long-term average 1 fatality per year and another SSAC = 1 building has a long-term average 5 fatalities per year, the second building would warrant higher priority for mitigation.

1.2 Agreement, objectives, and deliverables

This final report is delivered as a product of a cooperative agreement entitled "Developing Screening Criteria for Buildings at Risk from Seismic Damage," issued under the terms of the Rocky Mountains (RM) Cooperative Ecosystems Studies Unit (CESU), cooperative agreement number W912HZ-15-2-0033. The agreement specifies the following objectives and deliverables:

Objective 1. Research former USACE seismic building codes and determine if they meet the criteria for the HAZUS methodology building damages states. See section 2 for results.

Objective 2. Work with USACE engineers in developing the seismic hazard screening criteria for different building types that can be utilized in a database format such as Access or Oracle. The authors met in Walla Walla Washington on 18-22 Jan 2016 to develop the criteria documented here.

Objective 3. Provide technical expertise and research to determine how USACE buildings can utilize the FEMA HAZUS fragility curves, and provide suggestions if modifications are recommended, based on objective 1. Work with USACE engineers on developing methods for developing fragility curves, demand and capacity curves; determine the probability of reaching different damage states on an annualized basis. Provide technical expertise on how these seismic criteria best apply to USACE buildings to protect the public and Government property. This report documents the procedure we developed during our meeting of January 2016.

Deliverable 1. Draft Final Report. An electronic copy will be emailed to USACE Walla Walla District in the form of a Word document and a PDF should be submitted no later than one month before end of the project. At a minimum, the report shall contain an introduction section, and one section for each Task identified in the proposal. For each Task, the report shall summarize work accomplished for the Task.

USACE will review and provide comments, if any, within fifteen (15) calendar days after receipt. University of Colorado Boulder delivered the draft report on 25 Jun 2016.

Deliverable 2. Final Report. One (1) electronic copy of the final report, incorporating USACE review comments on the draft, if any, shall be submitted no later than fifteen (15) days after receipt of the USACE comments. Additionally, one (1) copy of the final report shall be submitted in a Word file(s) and in PDF, on digital media. University of Colorado Boulder received has no comments. This report therefore represents the final report.

1.3 Organization of the report

This section has introduced the problem to be addressed and the agreement under which we collaborated to meet the USACE's objectives. Section 2 addresses how to assign SSAC to non-essential facilities; section 3, essential facilities. Section 4 proposes one approach to estimating average annualized fatalities. Section 5 offers an algorithm for calculating average annualized repair cost. Sample calculations are presented in section 6. See section 7 for a glossary of technical terms and abbreviations. See section 8 for references cited. An appendix provides a brief note on gridded hazard data.

2. Non-essential facilities

Are non-USACE procedures for non-USACE buildings applicable to USACE facilities? That is, are USACE facilities significantly different from buildings built elsewhere in the US? We acquired USACE seismic building codes TM 5-809-10 April 1973 and TM-5-809-10 February 1982. The former uses allowable stress design similar to the contemporary Uniform Building Code (UBC) and SEAONC Blue Book. It expresses design base shear in the form V = ZKCW, where Z denotes a coefficient related to seismic zone (a geographic area of the United States, with regions of higher seismicity having higher values of Z), K is a coefficient to reflect the ductility and energy absorption characteristics of the structural system, the coefficient C parameterizes the effect of the period and stiffness of the structure in response to the ground motions, and W denotes dead load plus the expected value of live load. The parameters are so similar to those in the UBC that they would seem to satisfy the parameter requirements for Hazus-MH. The 1982 edition is similar but adds the parameters I and S, i.e., V = ZIKCSW. The parameter I reflects occupancy importance and S reflects site-structure resonance. Both new parameters are also similar or identical to contemporary UBC parameters and likewise will probably satisfy our needs for Hazus-MH. Therefore, let us feel free to apply methods and data developed for non-USACE buildings to USACE buildings.

FEMA P-154 (Applied Technology Council 2015) offers a similar system for rapidly screening buildings for potential seismic risk. In this paper-based screening methodology, one attempts to identify buildings that need detailed seismic evaluation and separate them from buildings that probably represent an acceptable life-safety risk. It employs a scalar score S that is generally in the range of 0 to 4 or more, where 0 is bad and 4 is good. The authors suggest a score of 2 as a breakpoint between buildings that require detailed seismic evaluation and those that probably pose an acceptable seismic risk. S reflects an estimate of the order of magnitude of collapse probability conditioned on risk-targeted maximum considered earthquake shaking, MCE_R. By "order of magnitude" is meant that a building with a score of *S* has a 10^{-S} probability of collapse in any particular portion, i.e., in the area occupied by any particular person. Thus, a building with a score of 2 poses a 10^{-2} or 1 in 100 probability of collapse in any particular portion of the building. Mathematically,

$$P\left[Collapse \middle| S_{M1} = x\right] = 10^{-S} \tag{1}$$

where P[A | B] means "the probability that A is true given that B is true" and S_{M1} is the 1-sec risk-targeted maximum-considered earthquake (MCE_R) shaking from ASCE 7-10. Equivalently,

$$S = -\log_{10}\left(P\left[collapse \middle| S_{M1} = x\right]\right) \tag{2}$$

The FEMA P-154 3rd Edition collapse probabilities are estimated using an enhancement to FEMA's Hazus-MH earthquake risk software. Hazus-MH uses structural engineering principles to calculate probabilistic damage to structural and nonstructural building components, as illustrated in Figure 1. The original Hazus-MH developers enhanced the software in recent years for the California Office of Statewide Health Planning and Development (OSHPD), the entity that regulates (among other things) the seismic safety of California hospitals. The enhancement allows for treatment of some readily observable features such as soft story and plan irregularities.

The two scoring systems seem somewhat parallel: 1 to 5 for SSAC and 0 to 4 (or so) for FEMA P-154. The latter has an engineering basis and relatively simple physical meaning that closely relates to seismic risk. It seems reasonable to relate the two with a simple 1-unit offset expressed in Equation (3) and equivalently in Table 1.

$$SSAC = round\left(S\right) + 1 \tag{3}$$

Table 1. Relating FEMA P-154 score S or Hazus collapse probability P to SSAC for non-essential facilities

SSAC	Approximately equivalent FEMA P-154 *S*	Range of FEMA P-154 *S*	Collapse probability P (from Equation 1)
1	0	S ≤ 0.5	P ≥ 0.3
2	1	0.5 < S ≤ 1.5	0.03 ≤ P < 0.3
3	2	1.5 < S ≤ 2.5	0.003 ≤ P < 0.03
4	3	2.5 < S ≤ 3.5	0.0003 ≤ P < 0.003
5	4+	3.5 < S	P < 0.0003

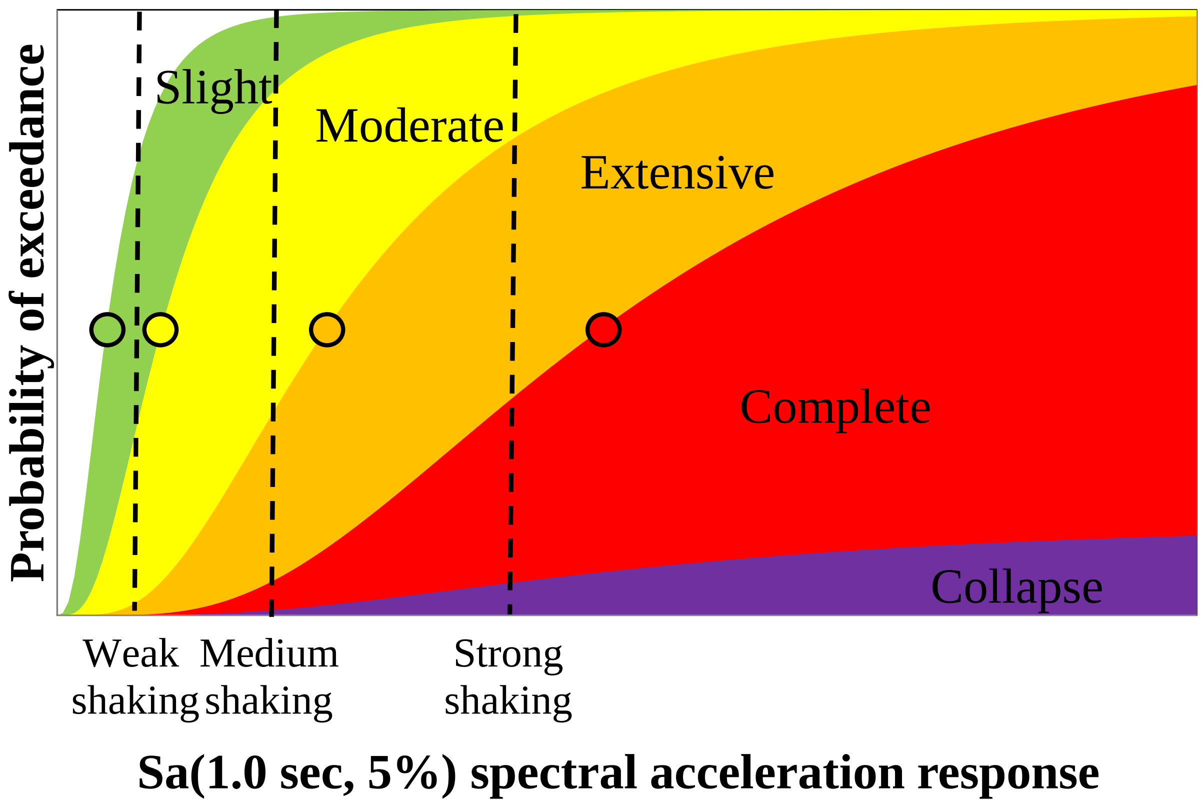

Figure 1. Hazus-MH damage states

3. Essential facilities

Essential facilities need to meet a higher performance objective than life safety; post-earthquake functionality is their objective, so a system for estimating post-earthquake functionality is desirable. We suggest that a functional building is one that has not been yellow or red-tagged under the ATC-20 post-earthquake safety evaluation system, and one whose equipment and necessary architectural systems are at most moderately, but not extensively, damaged, as illustrated in Figure 2. It is possible to use the Hazus-MH methodology to estimate these conditions.

We will use the Hazus fragility functions to calculate the probability that the building is not yellow tagged, and that the nonstructural drift-sensitive components (windows, doors, walls) are not extensively damaged, and that the nonstructural acceleration-sensitive components (mechanical, electrical, and plumbing equipment, suspended ceilings and above-ceiling systems) are not extensively damaged, and combine them as follows:

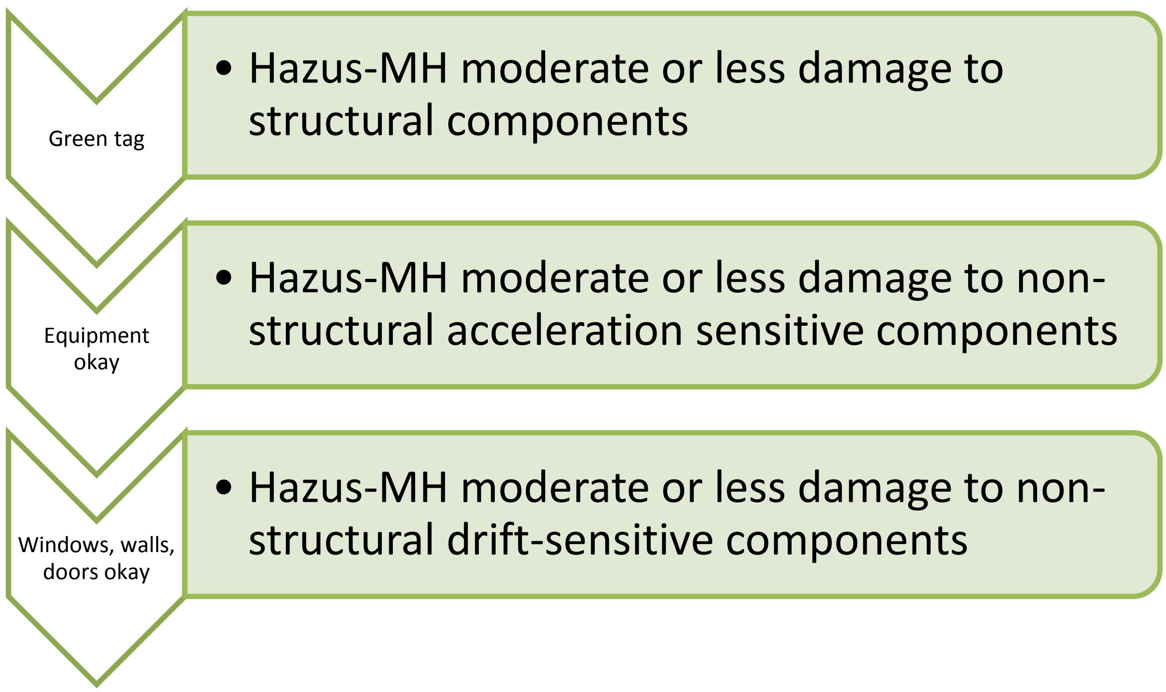

Figure 2. Requirements for an operational essential facility

$P[nonfunctional \mid S_{M1} = x] = 1 - P[functional \mid S_{M1} = x]$

$P[functional \mid S_{M1} = x] \approx$ P[not yellow tagged] · P[windows, walls etc. not extensively damaged] · P[MEP equipment, ceilings not extensively damaged]

$$P\left[nonfunctional \middle| S_{M1} = x\right] = 1 - \left(1 - P_{13}\right) \cdot \left(1 - P_{23}\right) \cdot \left(1 - P_{33}\right) \qquad (4)$$

S_{M1} = ASCE 7-10 MCE_R, 5 percent damped, spectral response acceleration parameter at a period of 1 s adjusted for site class effects

P_{13} = probability of reaching or exceeding extensive damage in structural component (proxy for yellow tagging)

P_{23} = probability of reaching or exceeding extensive damage of nonstructural drift-sensitive components (windows, walls, doors, etc.)

P_{33} = probability of reaching or exceeding extensive damage of nonstructural acceleration-sensitive components (e.g., MEP equipment, suspended ceilings, above-ceiling systems)

Then relate P[nonfunctional|S_{M1} = x] to SSAC as shown in Equation (5):

$$SSAC = round\left(-\log_{10} P\left[nonfunctional \middle| S_{M1} = x\right]\right) + 1 \quad (5)$$

Table 2 shows how functionality-based SSAC relates to ranges the probability that the facility is rendered nonfunctional given risk-targeted maximum considered earthquake (MCE_R) shaking.

Table 2. Relating probability that an essential facility is rendered nonfunctional to SSAC

P[*nonfunctional*|S_{M1}=*x*] (from Equation 4)	SSAC
P ≥ 0.3	1
0.03 ≤ P < 0.3	2
0.003 ≤ P < 0.03	3
0.0003 ≤ P < 0.003	4
P < 0.0003	5

4. Average annualized fatalities

To prioritize mitigation efforts within an SSAC or group of SSACs, one can calculate and consider average annualized loss (AAL) in terms of fatalities. Let us denote fatality *AAL* as AAL_f. Conceptually,

AAL_f = integral of (24-hour average number of occupants) · (frequency of shaking exactly equal to *x*) · (mean fraction of occupants killed when the facility is shaken at exactly *x*), integrated over all *x*

Mathematically,

$$AAL_f = V \cdot \int_{x=0}^{\infty} y(x) \left| \frac{dG(x)}{dx} \right| \cdot dx \tag{6}$$

Where

V = 24-hour average number of occupants

x = shaking intensity, which here is measured in terms of soil-amplified 1-second spectral acceleration response, S_a(1.0 sec, 5%), in units of g.

y(*x*) = mean fraction of indoor occupants killed when the facility is shaken at exactly severity *x*, from Hazus-MH plain-vanilla vulnerability functions (Porter 2009). Porter provided tables of *y*(*x*) in files named "Porter (20 Jan 2016) Hazus casualty vulnerability ordinary construction.txt" and "Porter (20 Jan 2016) Hazus casualty vulnerability special construction.txt." In those files, *x* is labeled "SA10" and indoor fatality rate *y*(*x*) is labeled "L4." See Porter (2009) Equation (26) for a reminder of how a value of L4 was calculated for one value of *x*.

G(*x*) = mean rate of shaking (events per year) of at least severity *x*, from US Geological Survey (USGS) National Seismic Hazard Mapping Program (NSHMP) gridded hazard curve data. The USGS provides the required data, but some manipulation is required. See Appendix 1.

To evaluate Equation (6) numerically, make tables of *y*(*x*) and *G*(*x*) at several standard values of x. Let us denote the values of x as $x_i \in \{x_0, x_1, \ldots x_n\}$, and the values of y(x) and G(x) at those values as $y_i \in \{y(x_0), y(x_1), \ldots y(x_n)\}$ and $G_i \in \{G(x_0), G(x_1), \ldots G(x_n)\}$. That is, y_i is shorthand for $y(x_i)$ and G_i is shorthand for $G(x_i)$.

$$\begin{aligned} AAL_f &= V\sum_{i=1}^{n}\left(y_{i-1}G_{i-1}\left(1-\exp\left(m_i\Delta x_i\right)\right) - \frac{\Delta y_i}{\Delta x_i} G_{i-1}\left(\exp\left(m_i\Delta x_i\right)\left(\Delta x_i - \frac{1}{m_i}\right) + \frac{1}{m_i}\right)\right) \\ &= V\sum_{i=1}^{n}\left(y_{i-1}a_i - \Delta y_i b_i \right) \end{aligned} \tag{7}$$

where

$$\Delta x_i = x_i - x_{i-1} \qquad \Delta y_i = y_i - y_{i-1} \qquad m_i = \ln\left(G_i / G_{i-1}\right) / \Delta x_i \text{ for } i = 1, 2, \ldots n$$

$$a_i = G_{i-1}\left(1-\exp\left(m_i\Delta x_i\right)\right) \qquad b_i = \frac{G_{i-1}}{\Delta x_i}\left(\exp\left(m_i\Delta x_i\right)\left(\Delta x_i - \frac{1}{m_i}\right) + \frac{1}{m_i}\right)$$

Equation (7) is exact for piecewise linear *y*(*x*), meaning linear between values of x_i, and piecewise loglinear *G*(*x*), meaning ln(*G*(*x*)) linear between values of x_i.

5. Average annualized repair cost

One can also calculate average annualized loss (AAL) in terms of repair cost per year. Let us denote repair-cost *AAL* as AAL_c. Conceptually,

AAL_c = integral of (building replacement cost new) · (frequency of shaking exactly equal to *x*) · (mean cost to repair the building as a fraction of its replacement cost new when the facility is shaken at exactly *x*), integrated over all *x*

Mathematically, the equation looks just like (6), except with different subscript in AAL and a different meaning for *V* and y(*x*):

$$AAL_c = V \cdot \int_{x=0}^{\infty} y(x) \left| \frac{dG(x)}{dx} \right| \cdot dx \qquad (8)$$

Where

V = replacement cost new of the building
x = same as before: shaking intensity, which here is measured in terms of soil-amplified 1-second spectral acceleration response, S_a(1.0 sec, 5%), in units of g.
y(*x*) = mean damage factor, which means the expected value of the repair cost as a fraction of replacement cost new when the facility is shaken at exactly severity *x*, from Hazus-MH plain-vanilla vulnerability functions (Porter 2009b). Porter provided tables of *y*(*x*) in files named "Porter (21 Jan 2016) Hazus damage factor vulnerability ordinary construction.txt" and "Porter (21 Jan 2016) Hazus damage factor vulnerability special construction.txt." In those files, *x* is labeled "SA10" and mean damage factor *y*(*x*) is labeled "MDF." See Porter (2009b) for a reminder of how a value of MDF was calculated for one value of *x*.
G(*x*) = as before: mean rate of shaking (events per year) of at least severity *x*, from USGS NSHMP gridded hazard curve data. The USGS provides the required data, but some manipulation is required. See Appendix 1.

To evaluate Equation (8) numerically, substitute the replacement cost new instead of 24-hour indoor occupants for *V* and the mean damage factor instead of fatality rate for *y*(*x*), and apply Equation (7).

6. Sample calculations

6.1 Sample calculation 1: non-essential building

Building NWW-LUC-002, built 1955, 11 occupants, 1 story, office building (COM1), lat = 43.765, lon = -116.188, site class D, model building type = MBT13-RM1, seismic design category C, SDS = 0.351, SD1 = 0.18, SS = 0.346, S1 = 0.114, no plan or vertical irregularities,

1. Hazus model building type, from Porter (20 Jan 2016) USACE MBTplus.xlsx: 1 story, 1955-> pre code, I = 1.0, → MBTplus = RM1Lp (Snplus = 29.4). Location puts it in the western US, "WUS."
2. P_{15}: From Porter (20 Jan 2016) Hazus collapse fragility functions ordinary construction.xlsx, RM1Lp. $S_{MS} = 1.5 \cdot 0.35 = 0.525$. $S_{M1} = 1.5 \cdot 0.18 = 0.27$. Look up RM1Lp, WUS, SA03 near 0.525: IM = "SA10" which means 1-sec spectral governs, so look up RM1Lp, WUS, SA10 ≈ 0.27. The nearest (SA10,P15) pairs are (0.24, 5.67E-3) and (0.28,5.67E-3). By linear interpolation, P15 = 3.35E-3 + (0.27 – 0.24)/(0.28 – 0.24)·(5.67E-3 – 3.25E-3) = 0.00517. But really we would use FEMA P-154 3rd Edition. Entering Table 1 with P = 0.00517, SSAC = 4.
3. From FEMA P-154 3rd Edition, Table A-1, SS = 0.346 → seismicity = "moderate," S1 = 0.114 → seismicity = "moderate." The map in FEMA P-154 says the county is moderately high, but site specific just moderate.
4. From FEMA P-154 3rd Edition, Appendix B, moderate seismicity form (PDF page 252), basic score = 2.1, no plan or vertical irregularities, pre-code (-0.2), S = 1.9. Entering Table 1 with S = 1.9, SSAC = 3. Versus SSAC = 4 from plain-vanilla Hazus collapse fragility.
5. Not essential, so no need to calculate P[functional].
6. Average annualized fatalities AAL_f = 0.5 per 100,000 per year. See Walton's spreadsheet us_hazardCurves.1hz.xlsx, tab Sheet3, although using the first row of the hazard spreadsheet, not the location where this building is.
7. Average annualized economic loss AAL_c = $49 for a $100,000 building, or $0.49/$1,000, which is the right order of magnitude. See us_hazardCurves.1hz.xlsx, tab Sheet4, although using the first row of the hazard spreadsheet, not the location where this building is.

6.2 Sample calculation 2: essential building

In San Francisco District (SPN), Building SPN-BYB-001, base yard building, built 1942, 15 occupants, 1 story, maintenance (COM2), essential facility, lat = 37.864, lon = -122.294 [this is the wrong place, the longitude has a typo], site class E, model building type = MB02, seismic design category F, SDS = 1.18, SD1 = 1.28, SS = 1.974, S1 = 0.801, FA = 0.90, FV = 2.4, no plan or vertical irregularities.

1. Hazus model building type, from Porter (20 Jan 2016) USACE MBTplus.xlsx: 1 story, 1942-> pre code, I = 1.0, → MBTplus = W2p (Snplus = 2.4). Location puts it in the western US, "WUS."
2. $P[Nonfunctional|S_{M1} = x]$: From Porter (20 Jan 2016) Hazus functionality fragility functions ordinary construction.xlsx, W2p. $S_{MS} = 1.5 \cdot 1.18 = 1.77$. $S_{M1} = 1.5 \cdot 1.28 = 1.92$. Look up W2p, WUS. The nearest (SA10, P13, P23, P33) vectors are (1.73, 0.905, 0.894, 0.333) and (1.94, 0.937, 0.928, 0.333). By linear interpolation, (P13, P23, P33) = (0.934,

0.925, 0.333). Evaluating Equation (4), P[*Nonfunctional*|S_{M1} = 1.92g] = 0.997. Entering Table 1 with P = 0.997, SSAC = 1.

3. Side note: P[*collapse*|S_{M1} = 1.94g] = 0.002, which would be SSAC = 4 for life-safety risk. This means the chance that any individual occupant would be killed when this building is shaken at S_{M1} = 1.94g is 0.002.
4. Side note: Take casualty vulnerability function L4 versus SA10 for W2p in WUS from "Porter (20 Jan 2016) (notes in table) HAZUS casualty vulnerability ordinary construction.xlsx." Result for 15 occs (3.6 equivalent full-time occupants) = 2.48E-5 = 2.48/100,000/pa = 0.7/100,000 people pa = 7x new building.
5. Side note: From damage factor ordinary construction, W2p, WUS, COM2, AAL_c = $350.04 for $100,000 replacement cost new, or $3.50 per $1000, which is high but not inconceivable for the San Francisco Bay Area

7. Glossary

AAL = average annualized loss, if one were to average the yearly loss considering the yearly chances of no shaking, weak shaking and loss, and strong shaking and loss.

Fragility function = probability that some undesirable event occurs as a function of environmental excitation, which here includes collapse probability as a function of 1-second spectral acceleration response, or probability of reaching or exceeding the structural extensive damage state as a function of 1-second spectral acceleration response, etc.

Hazus = software created with FEMA sponsorship that calculates natural-hazard risk from earthquakes, hurricanes, and floods. A tsunami model is also in development

MDF = mean damage factor, i.e., expected value of repair cost as a fraction of replacement cost new

MEP = mechanical, electrical, and plumbing components, such as packaged air conditioning units, electrical switchgear, and pumps.

Nonstructural acceleration-sensitive components = items such as suspended ceilings, mechanical, electrical, and plumbing equipment that are damaged when they are subjected to rapid acceleration as the floor or roof to which they are attached are shaken. Hazus treats these all as if they were a single thing in the building.

Nonstructural drift-sensitive components = items such as windows, walls and doors that are damaged when one story displaces laterally relative to another. Hazus treats these all as if they were a single thing in the building.

P[A | B] = probability that statement A is true given that statement B is true

SSAC = seismic safety action classification

Structural components = items such as beams, columns, shearwalls, braces and connections that provide the bulk of the strength and stiffness of the building. Hazus treats these all as if they were a single thing in the building.

S = FEMA P-154 3rd Edition final score, usually a number between 0 and 6, where 0 is bad, 6 is good, and 2 is the breakpoint between unacceptable and acceptable.

S_{M1} = 1-sec risk-targeted maximum-considered earthquake shaking from ASCE 7-10

Vulnerability function = a relationship between degree of loss (such as fraction of indoor occupants killed or repair cost as a fraction of replacement cost new) to environmental excitation (such as 5% damped 1-sec spectral acceleration response).

Yellow tag = a placard placed on a building after an earthquake by a building official or engineer deputized to act on behalf of the building official, indicating that the building's use is restricted, typically to prevent people from using a portion of the building or to limit the amount of time they can spend on the building, such as just to remove possessions

8. References cited

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Porter, K.A., 2009b. Cracking an open safe: more HAZUS vulnerability functions in terms of structure-independent spectral acceleration. *Earthquake Spectra* 25 (3), 607-618, http://www.sparisk.com/publications.

Appendix 1. Gridded hazard data

The US Geological Survey's National Seismic Hazard Mapping Program (NSHP) leads the country's efforts to estimate seismic hazard for purposes of building safety standards such as the ASCE 7-10 (American Society of Civil Engineers, 2010). As of this writing, the USGS provides gridded seismic hazard data for the entire US on 0.05-degree (~ 5 km) grid. Hazard is expressed in terms of exceedance probability, not exceedance frequency. Numerically the difference is very small, less than 1%, for probabilities in less than 0.01 (basically 100-year shaking or stronger), and less than 5% for exceedance probabilities less than 0.1 (10-year shaking or stronger). And since 10-year shaking is unimportant in the present application, there is no need to convert probability data to exceedance frequency data. However, the gridded hazard data is for site class BC (Vs30 = 760 m/sec), and would need to be adjusted for site amplification factors Fa and Fv.

As of this writing, USGS distributes its gridded hazard data from http://earthquake.usgs.gov/hazards/products/conterminous/2014/data/. If we measure shaking x in terms of 1-second spectral acceleration response, the data file needed for $G(x)$ is the one labeled "Data type = Hazard curve data; spectral acceleration = 1 Hz (1 sec), probability of exceedance = N/A, and the file size (in 2014) = 32.9 MB."