Risk-Targeted versus Current Seismic Design Maps for the Conterminous United States

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Abstract

The probabilistic portions of the seismic design maps in the NEHRP Provisions (FEMA, 2003/2000/1997), and in the International Building Code (ICC, 2006/2003/2000) and ASCE Standard 7-05 (ASCE, 2005a), provide ground motion values from the USGS that have a 2% probability of being exceeded in 50 years. Under the assumption that the capacity against collapse of structures designed for these "uniform-hazard" ground motions is equal to, without uncertainty, the corresponding mapped value at the location of the structure, the probability of its collapse in 50 years is also uniform. This is not the case however, when it is recognized that there is, in fact, uncertainty in the structural capacity. In that case, site-to-site variability in the shape of ground motion hazard curves results in a lack of uniformity.

This paper explains the basis for proposed adjustments to the uniform-hazard portions of the seismic design maps currently in the NEHRP Provisions that result in uniform estimated collapse probability. For seismic design of nuclear facilities, analogous but specialized adjustments have recently been defined in ASCE Standard 43-05 (ASCE, 2005b). In support of the 2009 update of the NEHRP Provisions currently being conducted by the Building Seismic Safety Council (BSSC), herein we provide examples of the adjusted ground motions for a selected target collapse probability (or target risk). Relative to the probabilistic MCE ground motions currently in the NEHRP Provisions, the risk-targeted ground motions for design are smaller (by as much as about 30%) in the New Madrid Seismic Zone, near Charleston, South Carolina, and in the coastal region of Oregon, with relatively little (<15%) change almost everywhere else in the conterminous U.S.

Introduction

In contrast to the seismic design maps in earlier editions of the NEHRP Provisions (and in the 1997 Uniform Building Code), which were loosely based on ground motion values with 10%-in-50-years exceedance probability, the probabilistic portion of the Maximum Considered Earthquake (MCE) ground motion maps in the 1997, 2000, and 2003 NEHRP Provisions (and all editions of the International Building Code) are equal to the 2%-in-50-years values. The associated increase in the ground motion values has been accompanied by a change in the performance objective from "life safety" to "collapse prevention," which led to the introduction of a factor of 2/3 that is applied to the MCE ground motion. This reduction factor is the reciprocal of *"a lower bound estimate of the margin [or factor of safety] against collapse inherent in structures designed to the Provisions. This lower bound was judged, based on experience, to correspond to a factor of about 1.5 in ground motion"* (p.17 of the 2003 NEHRP Provisions Commentary). Consequently, it was anticipated that in order to resist collapse under MCE ground motions, structures could be designed to 1/1.5=2/3 the MCE ground motion. Note that the uncertainty in the collapse capacity of a structure mentioned above in the abstract and described in a section below can be thought of as uncertainty in the 1.5 factor of safety.

As also explained in the commentary of the 2003 NEHRP Provisions, the BSSC Seismic Design Procedure Group (a.k.a. Project '97) that redefined the seismic design maps recognized that *"while [the earlier] approach provided for a uniform likelihood throughout the nation that the design ground motion would not be exceeded, it did not provide for a uniform probability of failure for structures designed for that ground motion"* (p.17). The estimated probability of collapse in 50 years for a structure designed for the 2%-exceedance-probability-50-years ground motions, with the 2/3 factor, is indeed more geographically uniform than that designed for the 10%-exceedance-probability-in-50-years ground motions, without any factor (Luco, 2006). Even so, significant variations in the probability of collapse remain when it is recognized that there is uncertainty in the collapse capacity (or in other words, in the factor of safety against collapse) relative to the ground motion for which the structure is designed. The variations in the probability of collapse arise from the coupling of this uncertainty with variations in the shape of ground motion versus exceedance probability hazard curves. These variations are particularly significant between locations in the western versus central and eastern U.S.

In pursuit of a geographically uniform (not to mention uniform across structural vibration periods) probability of failure, ASCE Standard 43-05 for seismic design of nuclear facilities has recently defined a simple design factor that,

when applied to the ground motion value at a specified exceedance probability (e.g., 10^{-4} per annum), results in a targeted probability of failure for the designed structure (e.g., 10^{-5} per annum). The design factor reflects the uncertainty in structural capacity and is a function of the approximate slope of the seismic hazard curve for the given location and vibration period. As part of the 2009 update of the NEHRP Provisions, which are expected to impact the 2012 International Building Code, the BSSC Seismic Design Procedure Review Group (a.k.a., Project '07) is investigating potential adjustments to the current definition of the seismic design maps, including adaptations of the ASCE 43-05 design factor for building code applications, in order to more consistently fulfill the stated intent of the NEHRP Provisions *"to provide uniform levels of performance for structures"* (p.17).

This paper explains the basis for these adjustments and demonstrates their quantitative effects on the seismic design maps. It starts by describing the "current seismic design maps," which would result in structures with uniform (within the probabilistic portions of the maps) collapse probability if the collapse capacity was not uncertain. Sources of the uncertainty in collapse capacity and a quantitative estimate of its magnitude are then discussed, followed by a description of a probability distribution for the uncertain collapse capacity. The calculation of collapse capacity using this probability distribution for the collapse capacity is then explained, followed by examples. Within the examples, adjustments to the ground motion values on the current seismic design maps that result in structures with uniform collapse probability are demonstrated. The paper concludes with a brief description of the resulting "risk-targeted" seismic design maps.

Basis of Current Seismic Design Maps

The seismic design maps in the 2006 International Building Code (and in the ASCE Standard 7-05 that it references) are identical to those in the 2003 NEHRP Provisions. Likewise, the seismic design maps in the 2003 and 2000 International Building Code (and the 2002 and 1998 editions of ASCE 7) are identical to those in the 1997 and 2000 NEHRP Provisions, respectively. Because the investigation of risk-targeted seismic design maps described in this paper is being conducted as part of the 2009 update of the NEHRP Provisions, the descriptions of and comparisons with "current" seismic design maps herein will refer to the maps in the 2003 NEHRP Provisions.

As explained in the commentary of the 2003, 2000, and 1997 NEHRP Provisions, *"in past [i.e., pre-1997] editions of the Provisions, seismic hazards around the nation were defined at a uniform 10 percent probability of exceedance in 50 years ..."* (p.17 of the 2003 edition), although the final values on

the seismic design maps were truncated at roughly one-half the hazard values along major faults in California and were increased elsewhere, sometimes significantly. The same is true for the seismic design maps in the most recent editions of the Uniform Building Code (1997) and Standard Building Code (1999), even though they post-date the 1997 NEHRP Provisions. Since the 1997 NEHRP Provisions, however, the seismic design maps have been redefined such that *"for most regions of the nation, the maximum considered earthquake [MCE] ground motion is defined with uniform probability of exceedance of 2 percent in 50 years"* (p.17). The change in the exceedance probability (from 10% to 2%) was *"responsive to comments that the use of 10 percent probability of exceedance in 50 years is not sufficiently conservative in the central and eastern United States where the earthquakes are expected to occur infrequently"* (p.321).

It is important to note, however, that the 2%-exceedance-probability-in-50-years ground motions are used only for *most* of the nation. Near known active faults, such as those in coastal California, the BSSC Seismic Design Procedure Group (Project '07) recognized that *"ground shaking calculated at a 2 percent probability of exceedance in 50 years would be much larger than that which would be expected based on the characteristic magnitudes of earthquakes on [the] known active faults"* that typically control the seismic hazard (p.17). The group considered it *"more appropriate to directly determine maximum considered earthquake ground motions based on the characteristic earthquakes"* (p. 17). Hence, wherever they are smaller, these so-called deterministic MCE ground motions are used in the seismic design maps instead of the probabilistic uniform-hazard (i.e., 2%-exceedance-probability-in-50-years) ground motions. This deterministic "capping" is considered to be more rational than the simple truncation formerly used for the pre-1997 editions of the NEHRP Provisions. For details on the deterministic ground motions, the reader is referred to the site-specific procedure in the 2003 NEHRP Provisions (Section 3.4), Appendix A of the commentary of the 2003 NEHRP Provisions, and an Earthquake Spectra publication by Leyendecker et al. (2000).

To show where the probabilistic versus deterministic ground motions are used in current seismic design maps, the ratio of the MCE ground motions in the 2003 NEHRP Provisions to the corresponding 2%-exceedance-probability-in-50years uniform-hazard maps produced by the USGS in 2002 (Frankel et al., 2002) is shown in Figure 1 for the conterminous U.S. The ratios for both the 0.2- and 1.0-second spectral (response) accelerations (for 5% of critical damping) maps are shown. Although the ratio is equal to unity for most of the nation – i.e., where the seismic design maps are equivalent to the uniform-hazard maps – it is less than unity along coastal California, in the New Madrid Seismic Zone,

and at a few other high-hazard locations – i.e., where deterministic ground motions are used. Note that the MCE ground motions in the seismic design maps can be as small as 0.4 times the uniform-hazard ground motions from the USGS.

In this paper we focus on the probabilistic portions of the current seismic design maps, under the assumption that the deterministic portions will continue to be treated as described above. Furthermore, our focus is on the mapped MCE ground motions (i.e., the S_S and S_1 values), before they have been adjusted for site class effects, reduced by the 2/3rds factor mentioned in the introduction, or extended to other structural periods via the design response spectrum. These approximate transformations of the mapped 0.2- and 1.0-second spectral accelerations for Site Class B to a design spectral acceleration at the fundamental period of the structure for the location-specific (or default) site class are presumed, for now, to be applicable to risk-targeted seismic design maps to the same extent that they are to the current maps.

If designing for the MCE ground motions (following the NEHRP Provisions in its entirety) were to result in structures that would (i) always, without a doubt, collapse if subjected to a spectral acceleration larger than the respective MCE ground motion, and (ii) never collapse under a smaller spectral acceleration, then the probability of such structure collapsing in Y (e.g., 50) years – hereafter referred to as the "collapse probability" – would be uniform within the probabilistic portions of the seismic design maps. This is because the probability of collapse would be equivalent to the probability of exceeding the MCE ground motion, which is defined to be uniform (i.e., 2% in 50 years). In reality, the threshold for collapse – i.e., the spectral acceleration (e.g., at its fundamental period) that the structure can resist without collapsing – is uncertain. More specifically, the collapse capacity is not deterministically equal to the corresponding ground motion value from the seismic design maps. As a result, designing for the MCE ground motions in the 2003 NEHRP Provisions does not result in buildings with uniform collapse probability, even within the uniform-hazard probabilistic portions of the seismic design maps. This lack of uniformity in collapse probability is also due to differences in the shapes of ground motion versus exceedance probability hazard curves. In fact, in the commentary of the NEHRP Provisions it is reported that *"because of these differences, questions were raised concerning whether definition of the ground motion based on a constant probability for the entire United States would result in similar levels of seismic safety for all structures"* (p.319 of the 2003 edition).

Uncertainty in Collapse Capacity of a Structure

As explained in the preceding section and demonstrated in a later section, designing for uniform-hazard ground motions (e.g., those in the probabilistic portions of current seismic design maps) does not result in structures with uniform collapse probability when it is recognized that the collapse capacity is uncertain. There are several reasons why the collapse capacity of a structure – i.e., the spectral acceleration (at its fundamental period) that it can resist without collapsing – is uncertain. Reasons for uncertainty in ground motion (spectral acceleration) *demand*, which are separate and encapsulated in the hazard curves used later in the paper, are not discussed here. The interested reader is referred to (Frankel et al., 2002).

One of the reasons for uncertainty in the collapse capacity is that the spectral acceleration associated with a ground motion that a structure can resist without collapsing will typically depend on other characteristics of the ground motion; in the limit, for example, it will depend on the entire waveform (e.g., the acceleration time history) of the ground motion. Since the waveform is uncertain, so is the corresponding spectral acceleration the structure can resist without collapsing. This source of uncertainty is often referred to as "record-to-record variability."

Another reason that the collapse capacity is uncertain is that, even if the other characteristics of the ground motion were known, the spectral acceleration associated with collapse will depend on the construction details of the structure. These details are uncertain due to variability in construction quality, material properties, nonstructural components, and other characteristics of the structure that are relevant to collapse. Since this source of uncertainty is largely due to lack of information (so-called epistemic uncertainty), it is more difficult to quantify. Nevertheless, it can contribute significantly to the total uncertainty in collapse capacity.

As with any random (i.e., non-deterministic) variable, the uncertainty in collapse capacity can be quantified by its standard deviation. For reasons that will become clear in the next section, we use the standard deviation of *the natural logarithm of* the collapse capacity, denoted β. Based in part on nonlinear dynamic structural analyses conducted by and referenced in the ATC-63 Project ("Quantification of Building System Performance and Response Parameters"), which is described in the next section, we estimate β to be 0.8. Although not shown in this paper, we also have considered $\beta=0.6$ and 1.0 as part of a sensitivity analysis, and find that the resulting risk-targeted seismic design maps are not significantly different overall.

Probability Distribution for Collapse Capacity

Since, as described above, the collapse capacity of a structure is not deterministic (i.e., not without uncertainty), it is logical to express it as a probability distribution. A commonly-used probability distribution for structural capacities is the lognormal distribution. Lognormal distributions are normally parameterized by a median (i.e., 50th-percentile value) and the aforementioned logarithmic standard deviation β (e.g., Benjamin and Cornell, 1970). However, they can instead be parameterized by β and any other percentile of the probability distribution – e.g., the 10th percentile. Later in this section we provide the probability distribution function (PDF) for the lognormal distribution written in terms of β and the 10th percentile value.

As explained in the preceding section, our best estimate of β for the collapse capacity is 0.8. For the 10th-percentile collapse capacity, we use an estimate that is based on state-of-the-art incremental dynamic analysis (Vamvatsikos and Cornell, 2002) of structures designed according to the present NEHRP Provisions, conducted by the FEMA-funded ATC-63 Project. The ATC-63 Project is (at the time of this writing) developing a methodology for more rational quantification of "seismic performance factors" used in design, including the response modification coefficient, or R factor. In order to establish acceptance criteria for seismic performance factors of new seismic-force-resisting systems proposed for construction and inclusion in model building codes and resource documents, or for re-evaluation of the seismic performance factors of existing lateral systems, the ATC-63 Project is determining the probability of collapse under the MCE ground motion for several archetypical code-compliant lateral systems.

It is important to note here that the "probability of collapse under MCE ground motion" is conceptually and numerically different than the "probability of collapse in 50 years" (or any other number of years). The former is the probability of the structure collapsing when it is subjected to the MCE ground motion, whereas the latter is the probability of the structure collapsing over a time span of 50 years, which depends not only on the former but also on the ground motion hazard (or probabilities) at the location of the structure. The former is the primary focus of the ATC-63 Project, whereas the latter is the ultimate concern in this paper.

Based in part on the computed probabilities of collapse under the MCE ground motion for several archetypical code-compliant lateral systems, in the ATC-63 Project an *"acceptably low probability of collapse is interpreted to be less than a 10% probability of collapse under the MCE ground motions"* (p. 2-19 of ATC-63 75% Draft). While this acceptance criterion is for new seismic performance factors,

it is also reflective of the observed performance of existing code-compliant lateral systems. In fact, it is consistent with the expected performance expressed in the Commentary of the 2003 NEHRP Provisions, namely that *"if a structure experiences a level of ground motion 1.5 times the design level [i.e., if it experiences the MCE ground motion level], the structure should have a low likelihood of collapse"* (p. 320). Based on the results of the ATC-63 Project, the "low likelihood of collapse" is approximately 10%.

Since collapse occurs when the collapse capacity is less than the ground motion demand, a 10% probability of collapse under the MCE ground motion indicates that the collapse capacity is less than the MCE ground motion with 10% chance, or in other words, that the 10th-percentile collapse capacity is equal to the MCE ground motion. More specifically, the MCE "ground motion" referred to here is the MCE spectral acceleration at the fundamental period of vibration of the structure, denoted S_{MT} in the ATC-63 75% Draft. Note that although S_{MT} at fundamental periods other than 0.2 and 1.0 seconds are not mapped in the NEHRP Provisions, they can be established by using the design response spectrum shape defined therein (e.g., pp. 38-39 of the 2003 NEHRP Provisions). Alternatively they may be established via a site-specific study. Hence, in this paper we take the liberty of using S_{MT} to denote the "mapped spectral acceleration" or "mapped ground motion."

Although not shown in this paper, the risk-targeted seismic design maps developed herein are more sensitive to the value of the 10th-percentile capacity, denoted hereafter as $c_{10\%}$, than they are to the value of β (the uncertainty in collapse capacity). While it is recognized that $c_{10\%}$ (not to mention β) can be different for different seismic-force-resisting systems, if not for different structures of the same system, we use the single best estimate $c_{10\%} = S_{MT}$. Since this "single" best estimate of $c_{10\%}$ is relative to the mapped ground motion, it takes on different values that depend on the location of the structure (not to mention its fundamental period). At locations where the mapped ground motion is relatively large, so is $c_{10\%}$, and vice-versa for relatively small mapped ground motions. Selecting a best estimate of $c_{10\%}$ is somewhat analogous to the current use in the NEHRP Provisions of a single factor of safety against collapse equal to 1.5 (i.e., the source of the single 2/3 factor applied to the MCE ground motion). As the Seismic Design Procedure Group that developed the current seismic design maps explains in the NEHRP Provisions Commentary, *"the SDPG recognizes that quantification of this margin is dependent on the type of structure, detailing requirements, etc., but the 1.5 factor is a conservative judgment appropriate for structures designed in accordance with the Provisions"* (p. 320 of the 2003 NEHRP Provisions Commentary). Whereas the 1.5 factor begets a single, deterministic collapse capacity equal to the MCE

ground motion, the reader is reminded that herein we fully recognize the uncertainty in the collapse capacity. We merely use a single best estimate for the 10th percentile of its probability distribution.

With the estimates of β (the uncertainty in the collapse capacity) and $c_{10\%}$ (the 10th-percentile collapse capacity) described above, an estimated lognormal distribution for the collapse capacity is fully defined. Its probability density function (PDF), denoted $f_{Capacity}(c)$, is given in Equation 1 and plotted in Figure 2.

$$f_{Capacity}(c) = \phi\left[\frac{\ln c - (\ln c_{10\%} + 1.28\beta)}{\beta}\right] \cdot \frac{1}{c\beta} \qquad (1a)$$

where

$$\beta = 0.8 \qquad (1b)$$
$$c_{10\%} = S_{MT} \qquad (1c)$$

and

$$\phi[\cdot] = \exp\{-[\cdot]^2 / 2\} / \sqrt{2\pi} \qquad (1d)$$

Note that $\phi[\cdot]$ is the standard normal (or Gaussian) PDF.

From Equation 1 it is clear that the probability distribution (or PDF) of the collapse capacity depends on the mapped ground motion spectral acceleration, namely S_{MT}. For structures designed using the MCE ground motions in the 2003 NEHRP Provisions, in the next section this collapse capacity PDF is used to calculate the probability of collapse in 50 years.

Calculation of Collapse Probability

As mentioned above in the introduction, if there were no uncertainty in its collapse capacity (i.e., if $\beta=0$), the probability of a given structure collapsing in Y years – abbreviated in this paper as the "collapse probability" – would be equal to the probability of the ground motion spectral acceleration (demand) at the structure's location exceeding the capacity value, also in Y years. This probability of exceeding a certain spectral acceleration value can be obtained from so-called hazard curves, such as those produced by the USGS (e.g., http://earthquake.usgs.gov/research/hazmaps/products_data/2002/hazcurve.php) or otherwise computed via site-specific probabilistic seismic hazard analysis (PSHA; Cornell, 1968; McGuire, 2004). Hence, the collapse probability could simply be read from a corresponding (i.e., for the same number of years and spectral acceleration vibration period) hazard curve.

Taking into account the uncertainty in the collapse capacity of a given structure described by Equation 1, the collapse probability can be calculated using Equations 2 and 3 below (e.g., McGuire, 2004).[1] Hereafter referred to generically as the "risk integral," Equation 2 couples the probability distribution for the collapse capacity with a corresponding ground motion (demand) hazard curve for the location of the structure. More specifically, the risk integral calculates the annual collapse probability, P[Collapse], by (i) considering every possible value of the uncertain collapse capacity, each denoted as c, (ii) obtaining the "conditional collapse probability" for each of these possible capacity values by reading from the hazard curve the annual probability that the spectral acceleration (demand) exceeds each the capacity value, P[$SA>c$], (iii) weighting these conditional collapse probabilities by the relative likelihoods (or probably densities) of the respective capacity values, $f_{Capacity}(c)$, and (iv) summing (or integrating) over all of these weighted, conditional collapse probabilities. Note that (ii) in this list is reminiscent of the hypothetical case of no uncertainty in the collapse capacity that is described at the beginning of this section. The uncertainty in the collapse capacity is dealt with in (i), (ii), and (iv).

$$P[\text{Collapse}] = \int_{0}^{\infty} P[SA > c] \, f_{Capacity}(c) \, \mathrm{d}c \qquad (2)$$

Restated more tersely, the risk integral calculates the collapse probability as an infinitesimal summation (or integration) of probabilities of collapse associated with each and every possible value of the collapse capacity. Each of these probabilities of collapse is equal to the probability that the ground motion demand exceeds the particular capacity value, multiplied by the probability of the capacity value. Let it be noted that the risk integral is simply an application of the theorem of total probability.

Let us also quickly note that strictly speaking it is more precise to express the risk integral in terms of mean annual frequencies (i.e., expected number of occurrences per year), rather than the annual probabilities P[·] (e.g., Der Kiureghian, 2005). However, numerically the two forms of the risk integral are practically equivalent. We have chosen to present Equation 2 in order to simplify the explanation of the collapse probability calculation.

To obtain a probability of collapse in Y years from the annual collapse probability calculated via Equation 2, one can use

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[1] Readers already familiar with the "risk integral" should note that the more well-known but equivalent form (e.g., in Luco, 2006) can be derived from Equation 2 via integration by parts.

Equation 3, which states that the Y-year collapse probability is equal to one minus the probability of the structure not collapsing in Y years, which in turn is equal to one minus the annual collapse probability multiplied Y times (or raised to Y-th power), assuming independence of the probabilities from year to year. While this simplifying assumption is not entirely accurate (e.g., Der Kiureghian, 2005), the large uncertainty in ground motion demand makes it more nearly so. Furthermore, our use of Equation 3 to roughly restate annual probabilities in terms of probabilities in Y years does not at all affect the risk-targeted ground motions that result. When Equation 3 is merely used to translate from one to the other, achieving uniform probability of collapse in Y years is equivalent to achieving uniform annual probability, and vice versa.

$$P[\text{Collapse in } Y \text{ years}] = 1 - (1 - P[\text{Collapse}])^{Y} \qquad (3)$$

In graphical form, several examples of calculating the collapse probability via the risk integral (and Equation 3) are provided in the ensuing sections.

Collapse Probability Examples

Using the risk integral described in the preceding section, here we present two examples of the calculation of the probability of collapse in 50 years ("collapse probability") of structures designed for the MCE ground motions in the 2003 NEHRP Provisions. In both examples, the fundamental period of vibration of the structure is 0.2 seconds. Although not shown here, the results for other periods exhibit very similar trends. The first example is for a location in the San Francisco Bay Area (SFBA; latitude=38.0, longitude= -121.7), and the second is for a site in the Memphis Metropolitan Area (MMA; latitude=35.2, longitude=-89.9), which is within the New Madrid Seismic Zone. The two locations are mapped in Figure 1. Although both are near the deterministic portions of the seismic design maps in the 2003 NEHRP Provisions, they are in fact within the probabilistic portions. The MCE spectral accelerations (at 0.2 seconds) for the SFBA and MMA locations are 1.38g and 1.29g, respectively. Despite the similarity in these mapped ground motions and, more importantly, the equality of their exceedance probabilities (i.e., 2% in 50 years), it will be seen that the corresponding collapse probabilities for the two locations are significantly different.

The evaluation of the risk integral for the SFBA and MMA locations is illustrated in Figure 3. The top panel of the figure shows the ground motion hazard curves for the two locations – i.e., P[$SA>c$], the annual probability that the spectral acceleration (at 0.2 seconds) exceeds the value c. These hazard curves are obtained from the 2002 USGS data (Frankel et al., 2002). Note the differences between their

shapes, which is typical of locations in the western versus central and eastern U.S. (e.g., Leyendecker et al., 2002; FEMA 351). As points of reference, the annual exceedance probability that is equivalent to 2% in 50 years and the corresponding MCE spectral accelerations (i.e., S_{MT} values) for the two locations are identified in the figure.

The middle panel of Figure 3 shows the probability distributions for the collapse capacity of the structure at each of the two locations – i.e., $f_{Capacity}(c)$, the probability density for the collapse capacity c, as expressed in Equation 1. Since the probability distribution of the collapse capacity depends on the mapped ground motion for which the structure is designed, the similarity in the MCE ground motions for the two locations (i.e., 1.38g for SFBA and 1.29g for MMA) results in similar probability distributions. The slightly larger MCE spectral acceleration for the SFBA location does, however, result in a probability distribution that is shifted slightly to the right, towards larger collapse capacities, relative to the MMA location.

The bottom panel of Figure 3 simply shows the product of the top and middle panels – i.e., the point-by-point product of the ground motion hazard curve $P[SA>c]$ and the probability distribution for the collapse capacity $f_{Capacity}(c)$ – which is the integrand of the risk integral. The area under each of the resulting curves is the collapse probability, as per the definition of an integral. Keeping in mind that the probability distributions of collapse capacity in the middle panel are substantially similar, and that the y-axis in the top panel is logarithmic in scale, it is apparent that the difference between the collapse probabilities is due primarily to the differences between the shapes of the hazard curves.

As noted in Figure 3, the calculated collapse probabilities for the SFBA and MMA locations are 1.1% and 0.7% in 50 years, respectively. As will be shown in the next section, the adjustments to the mapped MCE ground motions needed to make the collapse probabilities the same are significant (>15%). Although not shown here, there are locations in the conterminous U.S. for which the collapse probabilities of structures designed to the MCE ground motions in the 2003 NEHRP Provisions differ by almost a factor of four. The collapse probabilities for locations in the central and eastern U.S. tend to be smaller than those in the western U.S. (with some exceptions, e.g., coastal Oregon). Accordingly, the examples presented in this (and the next) section are representative of the entire U.S.

Risk-Targeted Ground Motion Examples

For the same SFBA and MMA locations and structures considered in the preceding section, we provide examples of the adjustments to the probabilistic MCE ground motions in

the 2003 NEHRP Provisions required to achieve a targeted collapse probability of 1% in 50 years. We choose this target risk not merely because 1% is a round percentage between the two collapse probabilities calculated in the preceding section, but because we have found that the average collapse probability in the probabilistic portions of the western U.S. is roughly 1% in 50 years, as obtained by repeating the calculations of collapse probability demonstrated in the preceding section for a fine grid of locations in the conterminous U.S.

The adjustments to the current (i.e., 2003 NEHRP) MCE ground motions that result in the targeted collapse probability of 1% in 50 years are back-calculated iteratively. The resulting "risk-targeted" mapped ground motions for the SFBA and MMA locations and structures are shown in Figure 4 which, like Figure 3 in the preceding section, illustrates the evaluation of the risk integral for the two locations, but for design using the risk-targeted rather than the MCE ground motions. The new ground motions for design are 1.44g and 1.04g at the SFBA and MMA locations, respectively, which correspond to adjustment factors of 1.04 and 0.81. In words, the MCE ground motion at the SFBA location need only be adjusted by a small amount to achieve a collapse probability of 1% in 50 years, whereas the MCE ground motion at the MMA location can be reduced significantly (i.e., by >15%).

As noted in the preceding section, the examples presented here for the SFBA and MMA locations are generally representative of the results for the western U.S. (perhaps excluding coastal Oregon) and the central and eastern U.S., respectively. Although not shown in this paper, relative to the MCE ground motions in the 2003 NEHRP Provisions, the risk-targeted ground motions for design are smaller (by as much as about 30%) in the New Madrid Seismic Zone, near Charleston, South Carolina, and to along coastal Oregon, with relatively little (<15%) change almost everywhere else in the conterminous U.S.

Conclusions

This paper explains the basis for proposed adjustments to the probabilistic portions of current seismic design maps (e.g., the MCE ground motion maps in the 2003 NEHRP Provisions) that result in a uniform estimated probability of collapse in Y (e.g., 50) years – or uniform "collapse probability" for short – of structures designed for the adjusted ground motions. The probabilistic "uniform-hazard" ground motions in current design maps only result in uniform collapse probability under the assumption that there is no uncertainty in the collapse capacity of a structure (i.e., the ground motion it can resist without collapsing), and that it is equal to the mapped ground motion for which it is designed.

Recognizing that there is, in fact, uncertainty in the collapse capacity, we make use of the so-called risk integral to first calculate estimated collapse probabilities for structures designed using the probabilistic MCE ground motions currently in the 2003 NEHRP Provisions, and then to back-calculate adjustments to these ground motions that result in uniform collapse probability. The risk integral couples probability distributions for the uncertain collapse capacity with the same seismic hazard curves from which the uniform-hazard ground motions (single points on the curves) are read.

To define the probability distributions of collapse capacity, we establish best estimates of the uncertainty in collapse capacity (β=0.8) and the 10th-percentile collapse capacity ($c_{10\%}=S_{MT}$, the mapped ground motion spectral acceleration at the fundamental period of vibration of the structure). These estimates are based in part on the findings of the ATC-63 Project, which performed nonlinear dynamic analyses of model structures designed according to the current NEHRP Provisions. The best estimates of β and $c_{10\%}$ improve upon the aforementioned assumption of no uncertainty in collapse capacity (i.e., β=0). Likewise, future refinements of β and $c_{10\%}$ (or any other percentile of the collapse capacity) might change the values of the adjustments to uniform-hazard ground motions, but the basis for these adjustments (that result in uniform collapse probability) would remain the same. At the time of this writing, we do not anticipate significant changes to the values of the adjustments, for two reasons. The first is that we have observed little sensitivity of the adjustments to candidate values of β between 0.6 and 1.0. Secondly, if the ATC-63 methodology for quantifying seismic performance factors is implemented in the development of new seismic regulations, S_{MT} will become an even better estimate of $c_{10\%}$ (because the ATC-63 acceptance criterion is a <10% probability of collapse under the MCE ground motion). If before then refinements to β and $c_{10\%}$ become available that are specific to a particular seismic-force resisting system, corresponding adjustments to uniform-hazard ground motions that are also specific to the particular system can be calculated.

As demonstrated in this paper with examples for two locations, one in the San Francisco Bay Area and the other in the Memphis Metropolitan Area, the calculated collapse probabilities for structures designed using the probabilistic portions of the MCE ground motion maps in the 2003 NEHRP Provisions tend to be smaller in the central and eastern U.S. (CEUS) relative to the western U.S (WUS). To result in a uniform collapse probability roughly equal to the current average across the WUS (i.e., 1% in 50 years), the adjustments to the MCE ground motions in the CEUS are generally in the range of factors of about 0.9 to 0.7. In the WUS, the factors are generally within a range of 0.9 to 1.15.

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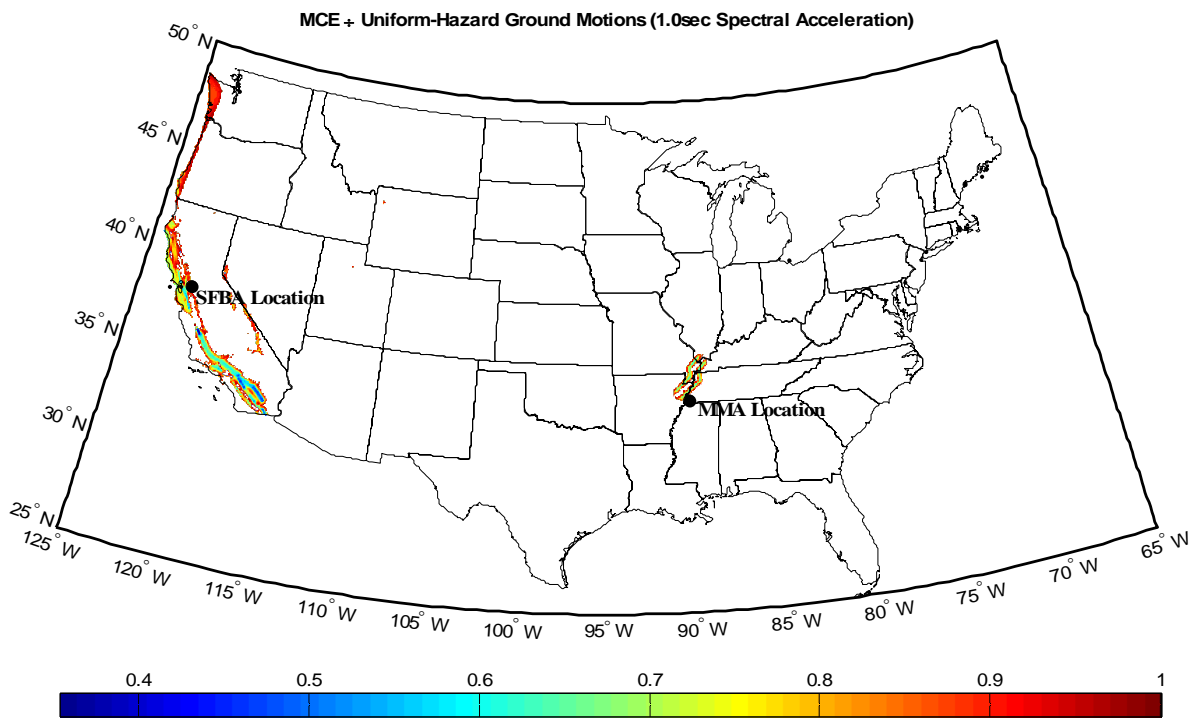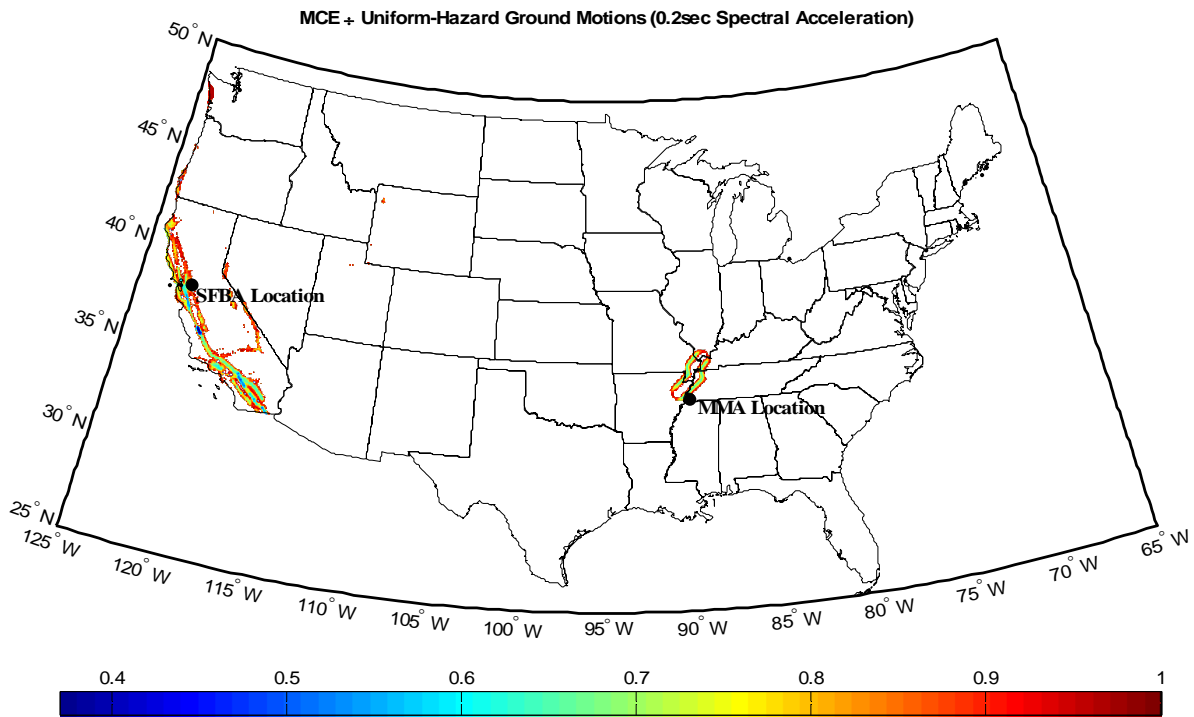
Figure 1. Maps of the ratio of the MCE ground motions in the 2003 NEHRP Provisions to the uniform-hazard (2% probability of exceedance in 50 years) ground motions from the USGS (Frankel et al., 2002). This paper focuses on the probabilistic portion of the current seismic design maps, shown in white.
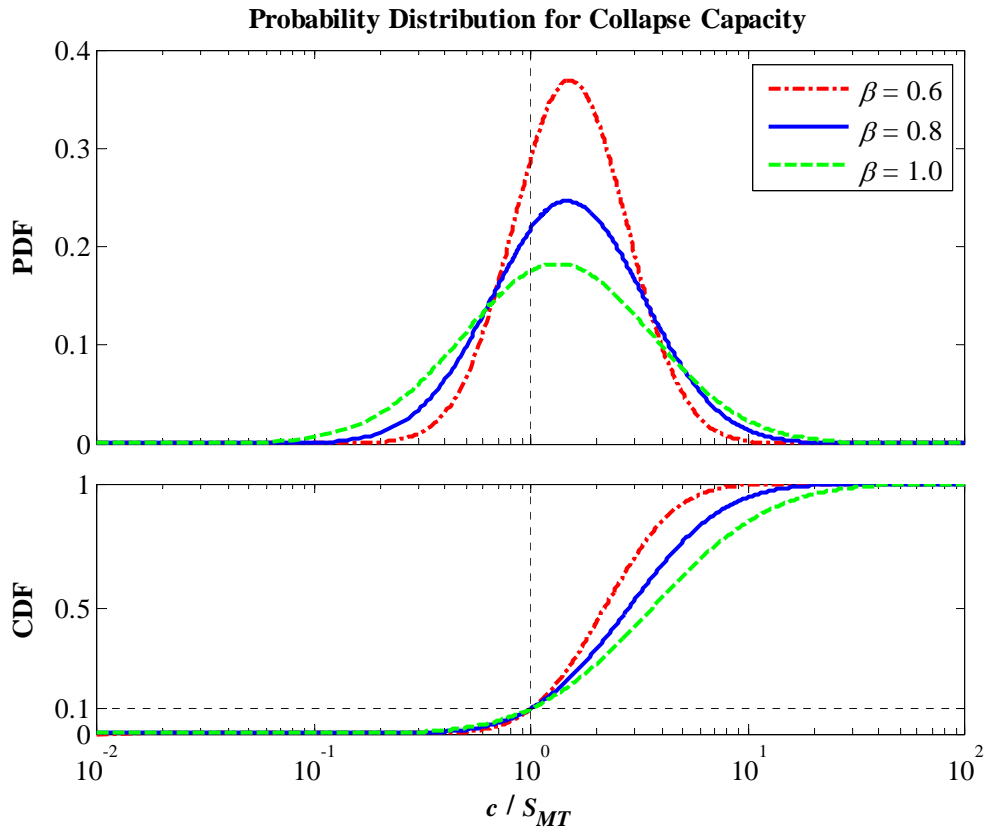
Figure 2. Probability density function (PDF) for the collapse capacity, as expressed in Equation 1. The three different amounts of uncertainty in the collapse capacity are the best estimate (β=0.8) and two extreme values considered in a sensitivity analyses. The cumulative distribution function (CDF) is shown to make it clear that the 10th-percentile collapse capacity is equal to the mapped (or MCE) spectral acceleration at the fundamental period of vibration of the structure, S_{MT}. The x-axis is logarithmic in scale so that each lognormal PDF appears as a normal (or Gaussian) "bell curve."
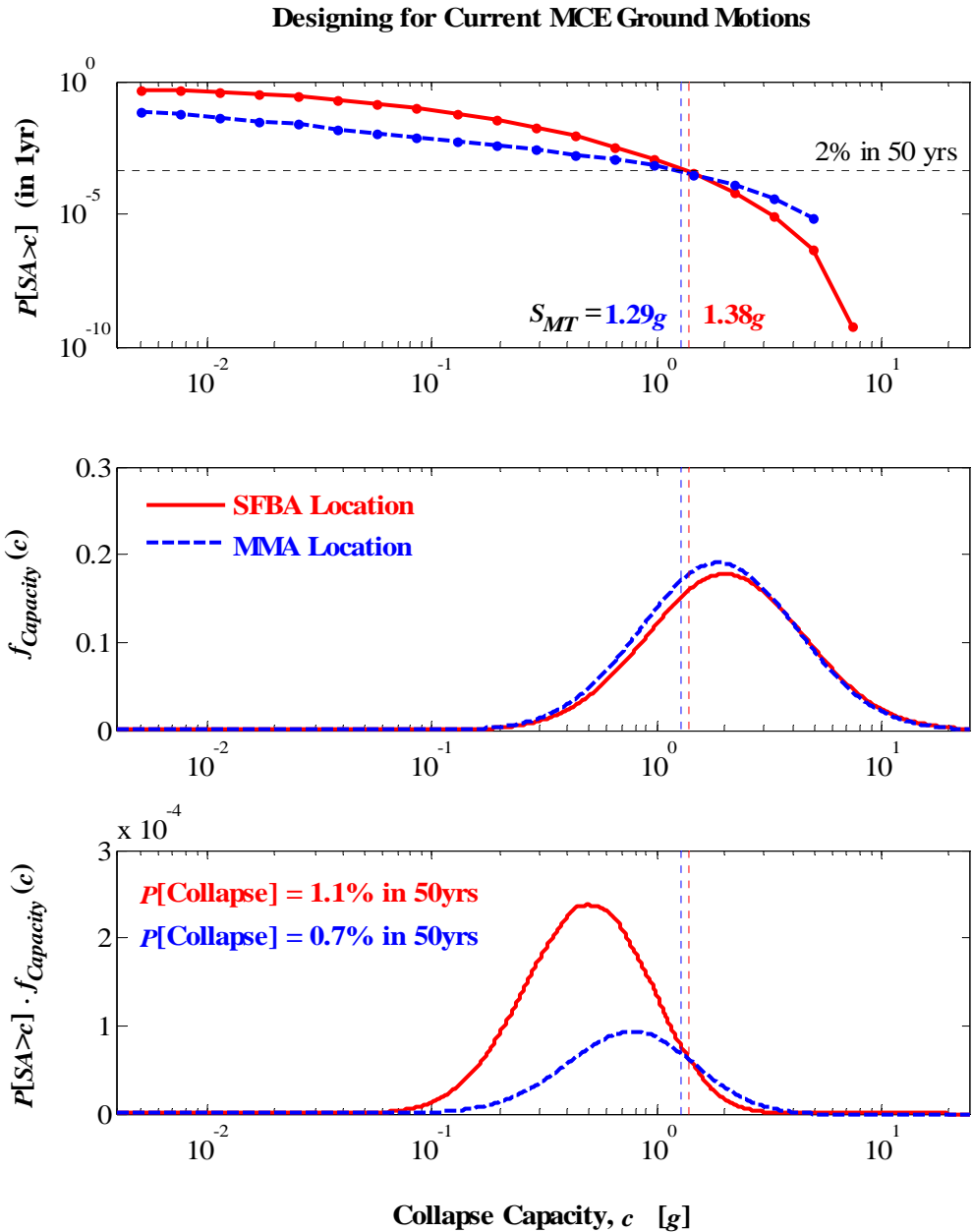
Figure 3. Two examples of the calculation, via the risk integral (Equation 2), of the probability of collapse in 50 years of a structure designed for the MCE ground motions in the 2003 NEHRP Provisions. The MCE ground motions (i.e., S_{MT} values) at the San Francisco Bay Area (SFBA) and Memphis Metropolitan Area (MMA) locations are 1.38g and 1.29g, respectively. The collapse capacities, denoted c, are values of spectral acceleration at 0.2 seconds, the fundamental period of vibration of the structure.
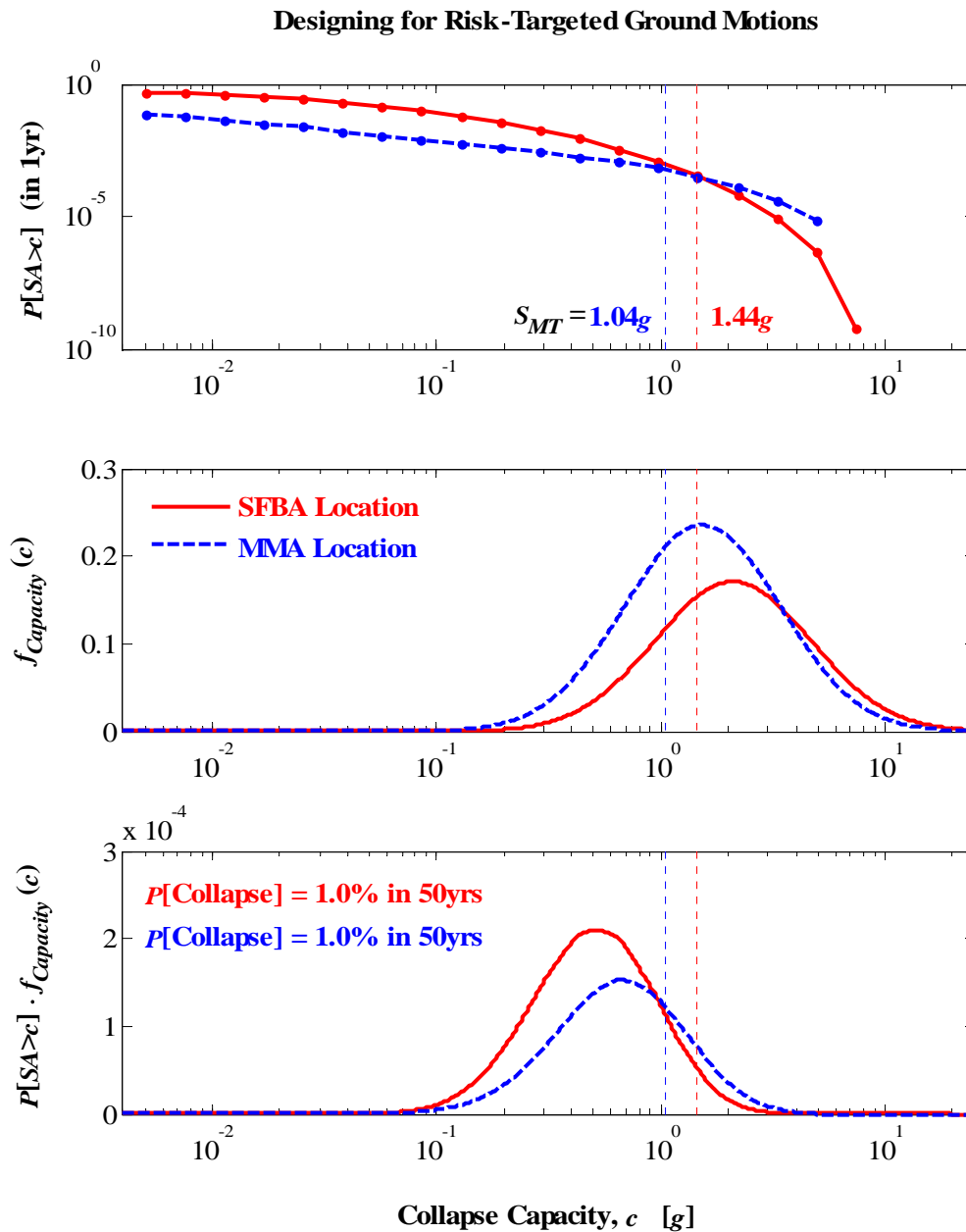
Figure 4. The counterpart to Figure 3 for the risk-targeted ground motions, which are back-calculated by iteratively adjusting the MCE ground motions until the calculated collapse probability is 1% in 50 years.