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RISK-CONSISTENT VERTICAL GROUND MOTION SPECTRA FOR SEISMIC PROBABILISTIC RISK ASSESSMENT

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ABSTRACT

Seismic Probabilistic Risk Assessment (SPRA) of nuclear power plants (NPPs) is typically performed using three major analysis components: probabilistic seismic hazard, seismic fragility, and plant response analyses. The seismic hazard output is used to construct a Reference Earthquake (RE) ground motion spectrum for seismic response analysis in the horizontal and vertical directions. The seismic response analysis develops the probability distributions of the RE seismic demands on the plant structures, systems, and components (SSCs). The seismic fragility analysis combines the RE demands with the probability distributions of the individual SSC seismic capacities to develop conditional probabilities of failure given the ground motion level. The plant response analysis combines the seismic fragilities of the SSCs into a single plant-level fragility. The seismic hazard curve is convolved with the plant-level fragility to quantify seismic risk, e.g., for core damage or large early release. The seismic hazard curve for a single "reference" ground motion parameter is typically used in the quantification. The reference ground motion parameter is often the horizontal peak ground acceleration (PGA) or sometimes the horizontal spectral acceleration (S_a) at a natural frequency that dominates the seismic responses of the SSCs that drive the risk. The outcome of the convolution integral is insensitive to the selection of this parameter if the slopes of the hazard curves for the range of applicable parameters are equal at return periods adjacent to the RE ground motion level. The seismic responses of the risk-dominant SSCs are typically considered to increase linearly with the reference ground motion parameter magnitude in the vicinity of the RE.

Selection of the RE ground motion spectrum is an important element in SPRA implementation. The amplitude of the RE is typically determined based on criteria for the horizontal ground motion, e.g., the horizontal uniform hazard response spectrum (UHRS) at a given mean annual frequency of exceedance (MAFE), and then the same criteria are applied for the vertical ground motion RE spectrum. Thus, the shapes of the horizontal and vertical RE are distinct, but their amplitudes are related, e.g., to the same MAFE. Since the seismic fragilities are reported and convolved with the hazard using a single reference parameter for horizontal ground motion, this reference parameter acts as a proxy for vertical ground motions when the seismic fragility of an SSC is strongly influenced by the latter. This proxy representation is valid if the slopes of the horizontal ground motion reference hazard curve and the hazard curves of the vertical ground motions that drive these fragilities are similar. When they are not, this proxy representation introduces bias in the risk quantification when these SSCs are risk-significant, and the corresponding fragilities should be adjusted to be risk-consistent. The need for such adjustment is often overlooked in the authors' experience with peer reviewing SPRAs. When considered, it is generally performed by reviewing the SPRA results to identify risk-significant SSCs that are significantly influenced by vertical ground motion and calculating SSC-specific adjustment factors to map the vertical ground motions that govern the fragility to the reference horizontal ground motion hazard curve. This process is iterative and subjective.

This paper introduces a method to systematically eliminate this potential bias in the fragility parameter by defining the RE vertical ground motion spectrum to be risk-consistent with the RE horizontal ground motions at all frequencies. The risk-consistent RE vertical ground motion spectrum is defined as the vertical ground motions for which the mean annual frequency of failure for a component governed by vertical ground motion input and convolved using the corresponding seismic hazard curve is equal to that computed using the convolution integral of the reference horizontal ground motion parameter used to define the seismic fragility and its corresponding hazard curve. This risk-consistent vertical ground spectrum is directly suitable for SPRA application. Seismic response analysis based on the risk-consistent ground motion spectrum eliminates the need to do case-by-case adjustments to specific SSC fragilities developed using hazard-consistent RE vertical ground motion as is common in current practice. This paper briefly introduces the risk-consistent RE vertical ground motion development method and presents example applications of the method to a case-study NPP site where the horizontal and vertical ground motion hazard curve slopes show significant differences. The examples validate the proposed vertical RE ground motion spectrum method and demonstrate the superior risk estimate compared to the traditional approach. The applicability of this method is valid for both SPRA and performance-based design criteria.

INTRODUCTION

Seismic Probabilistic Risk Assessment (SPRA) of nuclear power plants (NPPs) is typically performed using three major analysis components: probabilistic seismic hazard, seismic fragility, and plant response analyses. The seismic hazard output is used to construct a Reference Earthquake (RE) ground motion spectrum for seismic response analysis in the horizontal and vertical directions. The seismic response analysis develops the probability distributions of the RE seismic demands on the plant structures, systems, and components (SSCs). The seismic fragility analysis combines the RE demands with the probability distributions of the individual SSC seismic capacities to develop conditional probabilities of failure given the ground motion level. The plant response analysis combines the seismic fragilities of the SSCs into a single plant-level fragility. The seismic hazard curve is convolved with the plant-level fragility to quantify seismic risk, e.g., for core damage or large early release. The seismic hazard curve for a single "reference" ground motion parameter is typically used in the quantification. The reference ground motion parameter is often the horizontal peak ground acceleration (PGA) or sometimes the horizontal spectral acceleration (S_a) at a natural frequency that dominates the seismic responses of the SSCs that drive the risk. The outcome of the convolution integral is insensitive to the selection of this parameter if the slopes of the hazard curves for the applicable range of RE ground motion parameters are equal. The seismic responses of the risk-dominant SSCs are considered linearly proportional to the reference ground motion parameter magnitude in the vicinity of the RE.

Selection of the RE ground motion spectrum is an important element in SPRA implementation. The amplitude of the RE is typically determined based on criteria for the horizontal ground motion, e.g., the horizontal uniform hazard response spectrum (UHRS) at a given mean annual frequency of exceedance (MAFE), and then the same criteria are applied for the vertical ground motion RE spectrum. Thus, the shapes of the horizontal and vertical RE are distinct, but their amplitudes are related, e.g., to the same MAFE. Since the seismic fragilities are reported and convolved with the hazard using a single reference parameter for horizontal ground motion, this reference parameter acts as a proxy for vertical ground motions when the seismic fragility of an SSC is strongly influenced by the latter. This proxy representation is valid if the slopes of the horizontal ground motion reference hazard curve and the hazard curves of the vertical ground motions that drive these fragilities are similar. When they are not, this proxy representation introduces bias in the risk quantification when these SSCs are risk-significant, and the corresponding fragilities should be adjusted to be risk-consistent. This adjustment can be performed by reviewing the SPRA results to identify risk-significant SSCs that are significantly influenced by vertical ground motion and calculating SSC-specific adjustment factors to map the vertical ground motions that govern the fragility to the reference horizontal ground motion hazard curve. This process is iterative and subjective.

In addition to SPRA applications, this imitation in selecting vertical ground motions affects NPP design applications as well. The input ground motions for design of commercial NPPs in the U.S. are determined following ASCE/SEI 4-16 (ASCE, 2017) and ASCE/SEI 43-19[1] (ASCE, 2019). The design response spectra (DRS) are developed based on a target performance goal, which corresponds to a mean annual frequency of unacceptable performance. This process is typically applied to the horizontal UHRS to develop the DRS. It is common practice to either (1) develop the vertical DRS by applying vertical-to-horizontal (V/H) ratios to the horizontal DRS; or (2) apply the same frequency-dependent scale factors (SF) calculated for the horizontal DRS to develop the vertical DRS. Both methods result, essentially, in a vertical DRS hazard consistent with the horizontal DRS. The development of risk-consistent vertical ground motions for design requires (3) applying the V/H ratios to the horizontal UHRS at MAFE thresholds above and below the horizontal DRS, then using the DRS calculation process to interpolate between the resulting vertical UHRS independently. While the ASCE standards do not explicitly specify one method or prohibit the other, the authors' experience indicates that one of the first two procedures is typically followed, not the third one.

OBJECTIVE

This research aims to develop a process for defining risk-consistent vertical ground motion spectra. These spectra are applicable for use in SPRAs and in performance-based design of nuclear facilities, where the design is required to achieve a specified threshold for the annual probability of unacceptable performance. The discussion in this paper focuses on the SPRA application, e.g., RE spectrum, for conciseness. This discussion can be extended without much loss of generality to the performance-based design application, e.g., DRS.

CHARACTERIZATION OF SEISMIC HAZARD

The seismic hazard is represented by hazard curves, which define the MAFEs of S_a values for given spectral frequencies (Figure 1). Spectral acceleration values at a specific MAFE for a range of spectral frequencies define the corresponding UHRS shape. A reference ground motion parameter is selected, and the corresponding hazard curve is convolved with the component fragility curves to determine their probability of unacceptable performance (or failure), P_f. In early SPRAs, the reference ground motion parameter was traditionally selected to be the PGA. Recent SPRAs have recognized that it is more appropriate to select a reference ground motion representative of the spectral frequency range that drive the component responses whose failures dominate the seismic risk. The risk convolution integral is strongly influenced by the slope of the hazard curve. Therefore, the distinction is important if the slopes are significantly different in the ground motion ranges of interest to the SPRA.

When plotted on a log-log scale, hazard curves can often be adequately characterized as linear over an exceedance frequency range spanning a decade or less (Figure 1a). In SPRA applications, ground motions of meaningful contribution to risk typically span over one decade or slightly more. For the risk convolution integral, the reference hazard curve can therefore be represented within the ground motion range of interest by a linear segment in log-log space. Consider the ground motion range of interest to the plant-level fragility to span over one decade of exceedance frequencies, corresponding to MAFEs of H_P and H_D where $H_D = 10H_P$ (e.g., ASCE/SEI 43-19 selects $H_P = P_f$). Using the linear representation of the hazard curve between H_D and H_P, Kennedy and Short (1994) defined H(a), the mean annual frequency of exceedance of any ground motion within that range, $S_{a,H_D} \leq a \leq S_{a,H_P}$, using the following equation:

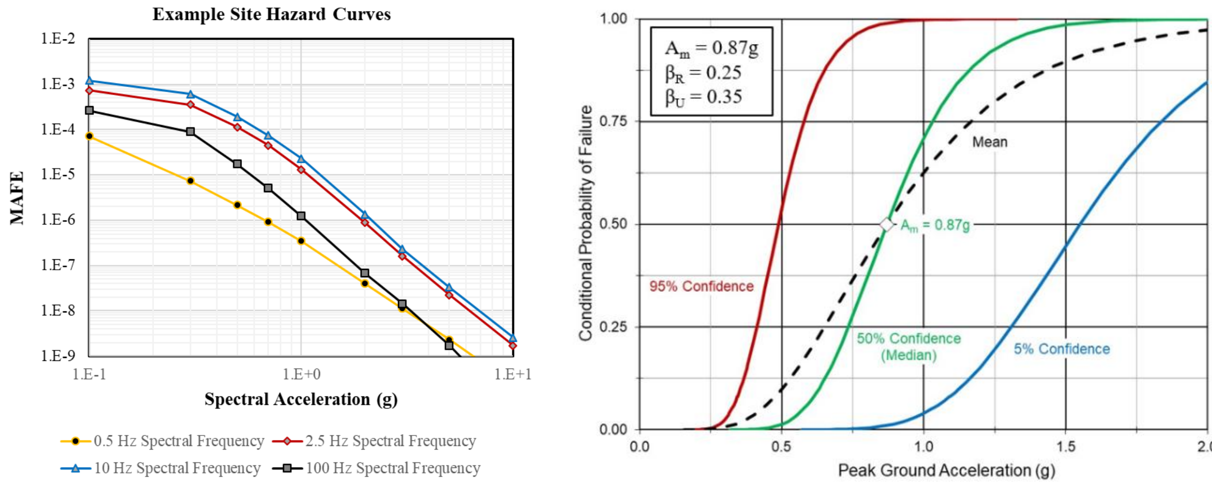
$$H(a) = K_1\, a^{-K_H} \tag{1}$$

[1] ASCE/SEI 43-19 contains the latest guidance from ASCE and is a major update from ASCE 4-98. It has been approved for publication by the ASCE Nuclear Standards Committee and is going through the copy-editing process.

where K_1 is the intercept, and K_H is the slope between H_D and H_P in log-log space, defined by:

$$K_1 = H(a = 1.0g) \tag{2a}$$
$$K_H = 1 / \log(A_R) \tag{2b}$$

where A_R is the ratio of ground motions S_{a,H_D} and S_{a,H_P}, and is a common indicator of the slope of the hazard curve across the one-decade mean return period. Larger A_R values correspond to flatter hazard curves.



(a) Seismic Hazard Curves (b) Seismic Fragility Curves

Figure 1. Demonstration Seismic Hazard and Fragility Curves

CHARACTERIZATION OF SEISMIC FRAGILITY

The seismic fragility of a structure or equipment component is defined as the conditional probability of its failure given the value of the reference ground motion parameter. The fragility family for a structure or component corresponding to a particular failure mode can be expressed in terms of the median ground motion capability, A_m, and two random variables, ε_R and ε_U.

$$A = A_m \varepsilon_R \varepsilon_U \tag{3a}$$
$$A_m = F_{Sm} A_{REF} \tag{3b}$$

where A_{REF} is the reference ground motion parameter value at the RE, F_{Sm} is the median scale factor at which the component seismic demands from the RE response analysis combined with non-seismic demand equals the median capacity for the failure mode of interest, and subscripts R and U refer to randomness and uncertainty variability sources (i.e., aleatory and epistemic). It is common to consider that these random variables follow lognormal probability distributions, with medians of 1.0 and logarithmic standard deviations β_R and β_U, respectively. The parameters A_m, β_R, and β_U fully define a family of fragility curves (Figure 1b). Each fractile fragility curve corresponds to a confidence level. The mean fragility curve can be shown to also follow a lognormal distribution with median A_m and logarithmic standard deviation β:

$$\beta = SQRT[\beta_R^2 + \beta_U^2] \tag{4}$$

QUANTIFICATION OF SEISMIC RISK

Seismic risk is defined as the annual frequency of unacceptable performance, i.e., failure, P_f. The mean risk is quantified by convolution of the mean seismic hazard and fragility curves. This convolution integral is developed takes the following mathematical form, per the seismic fragility methodology developed in EPRI TR-103959 (EPRI, 1994):

$$P_f = \int_0^\infty \frac{-dH(a)}{da} P_{f/a} da \tag{5}$$

Where, $P_{f/a}$ is the conditional probability of failure at a ground motion parameter value equal to "a", i.e., seismic fragility, and H(a) is the corresponding seismic hazard frequency of exceedance. Kennedy and Short (1994) derived the following expression for P_f as a function of the median capacity (A_m), logarithmic standard deviation (β), and the hazard curve parameters:

$$P_f = K_1 A_m^{-KH} \exp[0.5(K_H\beta)^2] \tag{6}$$

RISK-CONSISTENT VERTICAL GROUND MOTION

The objective of the SPRA is to quantify seismic risk. Overall plant risk depends on the plant response logic model. To that end, we consider risk consistency in the mean annual frequencies of failure for individual components, P_f. The typical seismic fragility evaluation proceeds as follows:

- Define horizontal and vertical RE spectra.
- Determine SSC median seismic responses and variability given the RE ground motion.
- Determine the probability distribution of the SSC seismic capacity, e.g., anchorage.
- Combine the SSC non-seismic demand with the demand from seismic response.
- Find the median RE scale factor F_{Sm} at which the median combined demand equals the median capacity.
- Combine the variabilities in demand and capacity to calculate β.

The seismic fragility is subsequently defined using the median ground motion capability and associated variabilities following Eqs. 3 and 4. Since the term A_{REF} corresponds to a horizontal ground motion parameter on the RE spectrum, A_m is expressed in terms of that ground motion. The SSC seismic risk computed in the SPRA quantification therefore involves the convolution of this fragility and the seismic hazard curve of the horizontal ground motion selected for A_{REF}.

$$P_{f,SPRA} = K_1 A_m^{-K_{Hh}} \exp[0.5(K_{Hh}\beta)^2] \tag{7}$$

If a given SSC failure mode is fully governed by the vertical ground motion, the true risk should be equal to the following convolution integral:

$$P_f = K_{1v} A_{mv}^{-K_{Hv}} \exp[0.5(K_{Hv}\beta)^2] \tag{8a}$$

$$A_{mv} = F_{Sm} A_{REF,v} \tag{8b}$$

where $A_{REF,v}$ is the vertical ground motion on the RE spectrum at the spectral frequency that drives the SSC response, and the subscripts "v" in the hazard curve parameters correspond to the seismic hazard curve of this vertical ground motion that corresponds to $A_{REF,v}$. The logarithmic standard deviation β is assumed to be equally expressed in terms of horizonal and vertical ground motions, which is practical and consistent with practice. A more rigorous fragility transformation where β is adjusted for the difference in hazard curve slope can be derived but must be applied on a component-by-component basis, which is not practical.

If the RE vertical ground motion is hazard-consistent, as is typically done, then the parameters A_{REF} and $A_{REF,v}$ will have the same MAFE. If the hazard curve slopes are different, then the seismic risk computed for the SPRA and the "true" seismic risk will typically be unequal. The bias in the calculated risk can be shown to be equal to the following expression:

$$P_{f,SPRA} / P_f = (F_{Sm})^{K_{Hv}-K_{Hh}} \exp[0.5\, \beta^2 (K_{Hh} - K_{Hv})] \tag{9}$$

Adjusting for this bias in the risk calculation can be done after the fact, but is tedious, seldom performed, and subjective to judgment of which SSCs are governed by which vertical ground motions and which spectral frequencies. This adjustment becomes tricky in situations where the governing failure mode has strong influences from both horizontal and vertical ground motions. An alternative and much more practical resolution is to select a RE vertical ground motion that is adjusted from the hazard-consistent spectrum, such that the resulting risk estimate $P_{f,SPRA}$ is equal to the true risk P_f for SSCs governed by vertical ground motions. Since this adjustment is applied to the entire RE vertical spectrum used in the seismic response analysis and is typically frequency-dependent, there is no need to identify which SSCs are governed by vertical ground motions or which spectral frequencies drive the response. These influences will be captured in the seismic response analysis and reflected in the seismic fragility. In addition, potential coupling effects between multiple frequencies or mixed influences of horizontal and vertical ground motions are seamlessly integrated. The following risk-consistent adjustment factor is derived. It is fully defined by the slopes of the reference horizontal and vertical hazard curves, β, and $F_{Sm.}$

$$\lambda = (P_{f,SPRA} / P_f)^{1 / K_{Hh}} \tag{10}$$

Details of the mathematical derivation are not shown here for brevity. The risk-consistent RE vertical ground motion spectrum is λ times the hazard-consistent vertical ground motion spectrum, where the adjustment factor λ is generally frequency-dependent since K_{Hv} is frequency-dependent. The dependence on β is not significant for the typical range of β, as shown in the next section. F_{Sm} should correspond to the expected median capacity of the plant-level fragility relative to the RE spectrum. While the plant-level fragility is not known a-priori before performing the SPRA, the RE spectrum is typically selected based on an estimate of the plant level fragility and expected risk, as discussed in EPRI 3002012994 (EPRI, 2018). Following this, the estimated median RE scale factor for the plant-level fragility can be determined and used to determine the risk-consistent vertical ground motion spectrum.

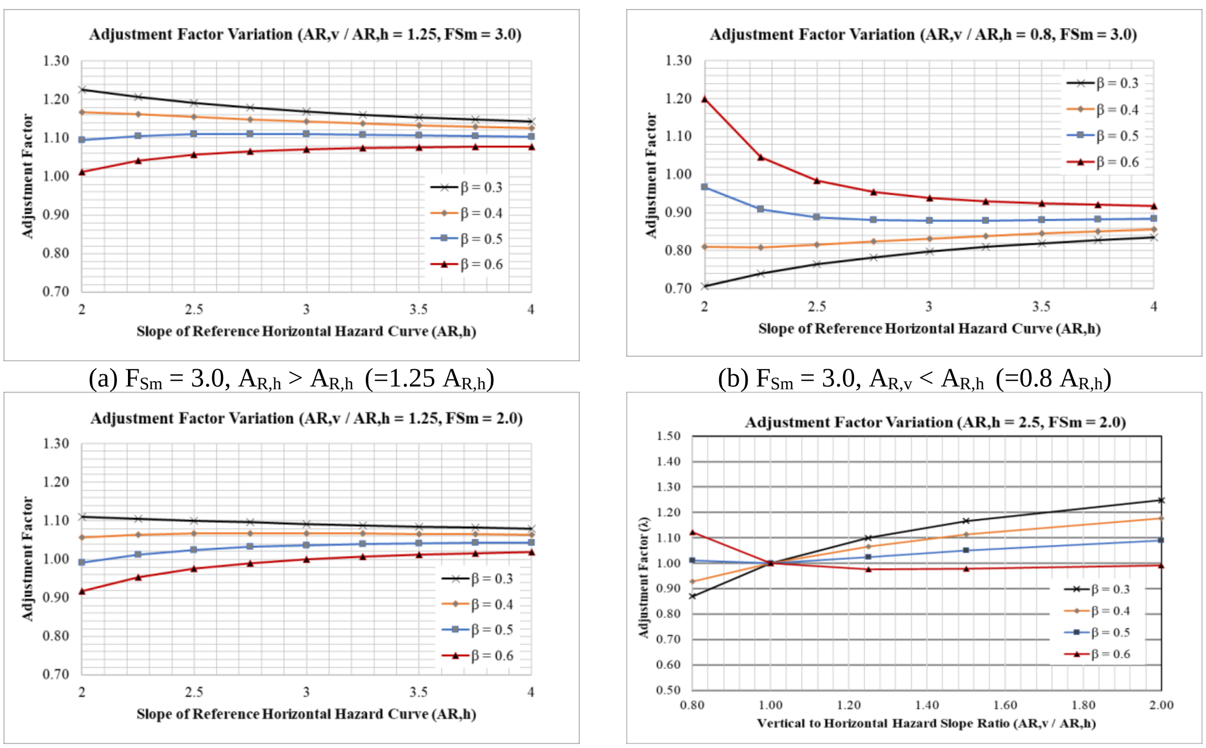
PARAMETERS THAT INFLUENCE THE RISK-CONSISTENT ADJUSTMENT FACTOR

Figures 2a and 2b show the influence of the ratio ($A_{R,v} / A_{R,h}$) when $F_{Sm} = 3.0$ for a typical range of β values as a function of $2 \leq A_{R,h} \leq 4$, which is a practical range for NPP SPRA applications in the U.S. When the vertical hazard curve slope is flatter than the horizontal (Figure 2a), a case more likely to occur than the opposite especially for soil sites, the factor λ is practically between 1.0 and 1.2 except for relatively small values of β and relatively steeper hazard curves ($A_{R,v} < 2.8$). Also, for relatively large β and steeper hazard curves, the factor λ may become less than 1.0. The increase in λ is inversely proportional to the fragility variability, β. However, the sensitivity to β is low within this range, such that λ can be estimated using a reasonable value of β and additional uncertainty added to the vertical ground motion based on the expected range of β. The differences in λ are much less significant than the typical variability in the V/H ratios, for which a minimum coefficient of variation (COV) of 0.25 is considered applicable per ASCE/SEI 4-16. Hence, the additional variability is minor and does not significantly influence the SPRA results. Since the values of λ are larger than unity in this range, ignoring the risk-consistent vertical ground motion adjustment factor would be unconservative if fragilities are not later adjusted.

When the vertical hazard curve slope is steeper than the horizontal (Figure 2b), the factor λ is largely between 0.75 and 1.0 in the range $2.0 \leq A_{R,h} \leq 4$ except for much steeper hazard curves ($A_{R,v} < 1.8$). The sensitivity to β is higher than the $A_{Rv} > A_{Rh}$ case (Figure 2a), and the value of λ increases with β.

However, for $A_{R,h} < 2.5$, the range of possible λ for reasonable β values is still significantly narrower than the typical variability in the V/H ratios. For $A_{R,h} < 2.5$ and $(A_{R,v} / A_{R,h}) = 0.8$ or lower, the slope parameter $A_{R,v} < 2.0$ is unrealistically steep and not likely to be encountered. Therefore, the large sensitivity exhibited by the factor λ in this range is not considered to be a realistic concern for SPRA. For design applications, a practical bound on the applicability of this factor may be imposed, which is beyond the scope of this paper. For both cases in Figures 2a and 2b, the influence of β on λ diminishes for flatter reference ground motion hazard curves i.e., as $A_{R,h}$ increases. In contrast, for steeper hazard curves, i.e., low $A_{R,h}$ and/or low ratio of $(A_{R,v} / A_{R,h})$, the sensitivity of the SPRA results to risk-consistent adjustment is more pronounced.

Figure 2c shows plots similar to Figure 2a, but for $F_{Sm} = 2.0$ to illustrate the influence of this parameter. The risk adjustment factors consistently decrease, by factors on the order of 10% compared to $F_{Sm} = 3.0$. The influences of Parameters β and $A_{R,h}$ are similar to Figure 2a. The λ plots for $F_{Sm} = 2.0$ and $A_{Rv} < A_{Rh}$ (not shown) predictably show a consistent increase in values compared to $F_{Sm} = 3.0$, on the order of 15%, and a similar sensitivity to β and $A_{R,h}$ to Figure 2b. Figure 2d shows a plot of λ as a function of the $(A_{R,v} / A_{R,h})$ ratio for a constant reference hazard curve slope parameter, $A_{R,h} = 2.5$, and $F_{Sm} = 2.0$. λ = 1.0 for a hazard curve slope ratio of 1.0. For a flatter vertical hazard curve, i.e., $(A_{R,v} / A_{R,h}) > 1.0$, the adjustment factor is essentially equal to or larger than unity and consistently increases (with a slight exception for relatively large β). As the slope ratio increases, the influence of β increases, but is still minor compared to the COV of 0.25 in V/H ratios. For a steeper vertical hazard curve, the pattern is reversed, again with the exception of relatively large β values. As observed in previous results, λ is more sensitive to low $A_{R,v}$ values.



(a) $F_{Sm} = 3.0$, $A_{R,h} > A_{R,h}$ (=1.25 $A_{R,h}$)

(b) $F_{Sm} = 3.0$, $A_{R,v} < A_{R,h}$ (=0.8 $A_{R,h}$)

(c) $F_{Sm} = 2.0$, $A_{R,v} > A_{R,h}$ (=1.25 $A_{R,h}$)

(d) $F_{Sm} = 3.0$, $A_{R,h} = 2.5$

Figure 2. Influence of Risk-Consistent Adjustment Factor Parameters

DEMONSTRATION EXAMPLES

Three examples are used to demonstrate the use and advantage of the risk-consistent adjustment factor λ. All three examples use the same site hazard. Figure 3 shows the Mean 1E-4 and 1E-5 5% damped horizontal and vertical UHRS for the site. The SSCs in the demonstration examples are housed in a single structure with a horizontal fundamental frequency of 20 Hz. The reference ground motion parameter for the SPRA in these examples is thus taken to be 20 Hz 5% damped spectral acceleration. Structure damping ratio is also 5%. The SSCs are all stiff and supported on a structural slab with dominant vertical frequency of 10 Hz. These SSC horizontal and vertical responses are thus driven by the respective 20 Hz and 10 Hz ground motions. Table 1 lists the relevant hazard curve parameters. The ratio ($A_{R,v}/A_{R,h}$) is about 1.50.

The SSC in each example is idealized as a single degree of freedom (SDOF) in each direction and assigned median in-structure capacities and a representative logarithmic standard deviation $\beta = 0.4$. The seismic fragility of each SSC is evaluated using the median scale factor on the RE demand, F_{Sm}, required to achieve the median capacity, and $\beta = 0.4$. The ground motions that contribute the most to the SPRA risk for the site are between 1E-4 and 1E-5 MAFE, a one-decade hazard interval. Three alternatives are considered for the RE horizontal and vertical ground motion spectra: (1) hazard-consistent spectra anchored to the Mean 1E-4 UHRS; (2) hazard-consistent spectra anchored to the Mean 1E-5 UHRS; and (3) Mean 1E-5 horizontal UHRS and risk-consistent vertical spectra, with $\lambda = 0.852F_{Sm}^{0.307}$ (Eq. 10), where F_{Sm} for calculating λ is based on the 1E-5 MAFE hazard-consistent RE demand, i.e., Case (2). The seismic fragility is then transformed into the horizontal A_{REF} corresponding to each RE case (Eq. 3b). The first example is used to validate the risk-consistent method against the true risk. The seismic risk is quantified for each RE case to demonstrate the bias involved in using the hazard-consistent RE vertical ground spectra. Figure 3 shows the resulting risk-consistent vertical spectrum for each demonstration example. In an SPRA project, only one RE vertical spectrum is used for the project based on F_{Sm} of the plant-level fragility.

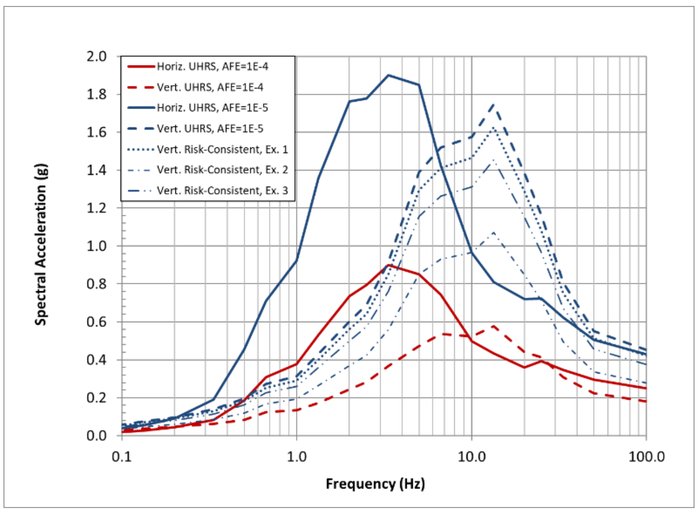


Figure 3. Ground Motion Spectra for Demonstration Examples

Table 1: Selected Seismic Hazard Parameters

Ground Motion (g)	1E-4 MAFE	1E-5 MAFE	A_R	K_1 (/yr)	K_H
20 Hz Horizontal	0.360g	0.720g	2.003	3.37E-6	3.016
10 Hz Vertical	0.523g	1.576g	3.012	2.58E-5	2.089

Table 2: Summary of Demonstration Example Risk Estimates

Example #	1	2	3	1	2	3
Reference Earthquake	**Mean Risk (/yr)**			**Ratio to RE_3 Risk Estimate**		
Exact Solution	8.6E-06	N.A.	N.A.	1.00	N.A.	N.A.
RE_1 (1E-4 UHRS)	2.8E-06	3.4E-04	1.6E-05	0.33	1.05	0.74
RE_2 (1E-5 UHRS)	1.1E-05	4.6E-04	3.0E-05	1.27	1.42	1.35
RE_3 (Risk-Consistent)	8.6E-06	3.2E-04	2.2E-05	1.00	1.00	1.00

Example 1 – Component Governed by Vertical Ground Motion

Examples of SSCs governed by vertical ground motions include horizontally-oriented valves yokes and out-of-plane shear failure in reinforced concrete slabs. For this example, a structural slab median shear strength is reached when the vertical zero-period acceleration (ZPA) of the floor reaches 2.0g in addition to gravity load. The vertical floor ZPA is equal to the 10 Hz vertical ground spectral acceleration. This results in a median RE scale factor $F_{Sm,1} = 3.820$ and $F_{Sm,2} = 1.269$ for RE alternatives 1 and 2 (RE_1 and RE_2), respectively. For RE_3, which is risk-consistent with the 1E-5 MAFE horizontal spectrum, $\lambda = 0.852(1.269)^{0.307} = 0.930$. The corresponding risk-adjusted $F_{Sm,3}$ for $RE_3 = 1.269 / \lambda = 1.364$, i.e., less than 10% higher than the corresponding hazard-consistent RE scale factor, $F_{Sm,2}$.

The true risk estimate of the slab shear failure is quantified by convolving the seismic fragility expressed in terms of the governing vertical ground motion, i.e., $A_{m,v}$= 2.0g, $\beta = 0.40$, according to Eq. 6 and substituting the 10 Hz vertical hazard curve parameters from Table 1, which yields 8.6E-6/yr. The risk estimates using RE alternatives 1, 2, and 3 are calculated using Eq. 6 and the median capacities expressed in terms of the reference 20 Hz horizontal ground motions and substituting the corresponding hazard curve parameters from Table 1. These respective median capacities are the products of $F_{Sm,i}$ and the corresponding RE horizontal ground motions of 0.360g, 0.720g, and 0.720g, respectively. Table 2 compares the results of these risk estimates. It is clear that hazard-consistent RE_1 and RE_2 introduce significant unconservative and conservative biases in the risk estimate, and that the risk-consistent RE_3 results in an exact estimate. The bias in this case is extreme, since the component in this illustrative example is governed only by vertical ground motion, which is an uncommon occurrence. The next examples present more typical occurrences.

Example 2 – Unanchored Component Governed by Sliding

The second example is a stiff unanchored component whose fragility is governed by the initiation of sliding. For this example, the median strength is computed by considering a median coefficient of friction of 0.4. The horizontal and vertical floor ZPAs represent the component demands, and are equal to the ground spectral accelerations of the 5% damped RE horizontal and vertical spectra at 10 and 20 Hz, respectively (Table 1). The maximum horizontal and vertical forces on the component are combined using the 100-40-40 combination, which is permitted by ASCE/SEI 4-16 and considered to be median-centered. The effective coefficient of friction concurrent with the maximum horizontal force is calculated by reducing the component weight by 40% of the maximum seismic vertical force.

A two-dimensional sliding evaluation is performed for simplicity, i.e., the minor horizontal acceleration component is ignored. This results in median RE scale factors $F_{Sm,1} = 0.9025$, $F_{Sm,2} = 0.4115$, and $\lambda = 0.613$. The factor λ is remarkably low due to the low $F_{Sm,2}$ and the relatively high ($A_{R,v}/A_{R,h}$) ratio. However, the vertical ground motion influence on this seismic fragility is secondary to the horizontal. Using the 1E-5 MAFE horizontal UHRS and 0.613 times the 1E-5 MAFE vertical UHRS spectral accelerations to represent the risk-consistent RE seismic demands and combining by 100-40-40, the risk-consistent median RE scale factors $F_{Sm,3}$ is found to be 0.4574, i.e., still only about 10% higher than the corresponding hazard-consistent RE scale factor, $F_{Sm,2}$.

The true risk estimate cannot be quantified in closed form similar to the previous example, since the SSC sliding fragility is significantly influenced by both the horizontal and vertical ground motions rather than by one single ground motion and the corresponding hazard curve. The risk estimates using RE alternatives 1, 2, and 3 are calculated using Eq. 6 and median capacities of 0.324g, 0.296g, and 0.329g in terms of 5% damped 20 Hz horizontal ground motions, respectively. Table 2 compares the resulting risk estimates. Both RE_1 and RE_2 result in conservative risk estimates, with the latter being farther apart from the risk-consistent estimate based on RE_3. RE_2 and RE_3 both use the same horizontal ground motion spectrum, the Mean 1E-5 UHRS, and only differ in the vertical spectrum being hazard- or risk-consistent.

Example 3 – Anchored Component Governed by Anchor Bolt Tension

The third example is a stiff anchored component whose fragility is governed by anchor bolt tension. Shear is resisted by shear lugs, such that anchor bolts resist tension only. For this example, the median anchor bolt strength is reached if (1) floor horizontal ZPA alone reaches 1.0g; (2) floor vertical ZPA alone reaches 2.0g; or (3) the square-root-of-the-sum-of-squares (SRSS) combination of the bolt demand-to-capacity ratios (DCRs) from horizontal and vertical ZPAs reaches 1.0. The RE floor ZPAs are the same as Example 2. The ratios of the governing vertical to horizontal ground motions (Table 1) are about 1.5 and 2.2 for RE_1 and RE_2, respectively, i.e., the anchor bolt DCRs from horizontal and vertical ZPAs are comparable. This results in median RE scale factors $F_{Sm,1} = 2.249$, $F_{Sm,2} = 0.9369$, and $\lambda = 0.832$. Using the 1E-5 MAFE horizontal UHRS and 0.832 times the 1E-5 MAFE vertical UHRS spectral accelerations to represent the risk-consistent RE seismic demands and combining by SRSS, the risk-consistent median RE scale factors $F_{Sm,3}$ is found to be 1.027, i.e., also about 10% higher than the corresponding $F_{Sm,2}$. The risk estimates using RE alternatives 1, 2, and 3 are calculated using Eq. 6 and median capacities of 0.809g, 0.675g, and 0.739g in terms of 5% damped 20 Hz horizontal ground motions, respectively. Table 2 compares the resulting risk estimates. The risk numbers estimated using RE_1 and RE_2 have biases of about 30% in the unconservative and conservative directions, respectively.

CONCLUSION

A practical approach for developing a risk-consistent RE vertical ground motion spectrum was introduced. This approach is applicable to both SPRA and performance-based design applications. The risk-consistent vertical ground motion spectrum is the frequency-dependent factor, λ, times the hazard-consistent spectrum. The factor λ is defined by the slopes of the hazard curves and the estimated plant-level fragility curve. The influence of these parameters was reviewed and discussed. The development and implementation of λ was validated using a case study demonstration example with a known solution. The validation and subsequent demonstration examples showed the bias in risk estimates developed based on hazard-consistent RE ground motion spectra compared to the risk-consistent spectrum for three classes of component fragilities governed by vertical only, sliding, and anchor bolt tension. For this example, the contributions of horizontal and vertical ground motions to the anchor bolt seismic demand were comparable. Results will vary for other ratios of bolt demands due to horizontal and vertical motions.

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