Full Paper Transactions, SMiRT 28
Toronto, Canada, August 10-15, 2025

RISK-INFORMED PERFORMANCE-BASED DESIGN USING SEISMIC MARGINS

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ABSTRACT

This paper presents a proposed approach to define a risk-informed performance based (RIPB) seismic design basis. Performance goals can be classified into scenario-based and annual frequency-based targets. A scenario-based performance goal requires that the reactor design demonstrates the ability to maintain its required safety and mitigation functions with acceptable confidence when it experiences a given earthquake that exceeds its design basis. It is typically demonstrated using seismic margin assessment (SMA) or probabilistic safety-assessment (PSA)-based SMA methodology. The plant-level high confidence of low probability of failure (HCLPF) capacity is the typical metric of seismic margin used in both methodologies.

An annual frequency-based performance goal requires that the design demonstrates an acceptable annual frequency of "failure," where the definition of failure can range from yielding or collapse of a structure to inability to o maintain the required safety and mitigation functions (e.g., core damage or other accident sequence frequencies) for nuclear facilities. For nuclear facilities, this is typically demonstrated using seismic probabilistic safety assessment (SPSA) methodology. SMA, PSA-based SMA, and SPSA are well established methodologies. SPSA methodology is considerably more effort-intensive than the other two. In addition, advanced reactor designs are becoming increasingly more seismically robust. Consequently, their annual frequency-based performance metrics involve considerable contributions from exceedingly rare ground motion magnitudes where the current understanding of both the hazard and plant response to earthquake effects involve large uncertainties that are not conducive to the stability and reliability of a design process.

The International Atomic Energy Agency (IAEA) TE-2043 developed a technique to determine the seismic margin required to achieve a target annual frequency of unacceptable performance. This margin is determined on a site- and design-specific basis using the closed-form risk integral equation in Kennedy and Short (1994) and demonstrates limited sensitivity to uncertainty. This paper leverages the elements of this technique to propose an efficient determination process for the seismic design basis hazard level of individual structures, systems, and components (SSCs) designed following RIPB codes and standards, like ASCE/SEI 43 and ASCE/SEI 7, both published by the American Society of Civil Engineers (ASCE) Structural Engineering Institute (SEI). The concept and implementation process described in this paper can be readily extended to determining the design basis level for other external hazards like wind.

OVERVIEW

This paper starts by introducing the motivation. It proceeds to summarize the technical basis for the development of seismic margin-based nuclear installation design adequacy recommendations developed in IAEA TE-2043 (2024). The paper then discusses how to leverage the technical basis for TE-2043, which was developed for nuclear installation design robustness and safety review, to develop an RIPB design basis hazard level for individual SSCs. Finally, the paper demonstrates the application of this process to the ASCE/SEI 43 and ASCE/SEI 7 design standards, which can be used as examples for other RIPB design codes.

MOTIVATION

RIPB design applications are increasingly desirable for nuclear installations. A particular milestone in this regard is the publication of Nuclear Energy Institute (NEI) 18-04 (2018) guidance and its endorsement by the U.S. Nuclear Regulatory Commission (USNRC) in Regulatory Guide (RG) 1.233 (2020). This design approach utilizes probabilistic safety analysis to inform the safety classification, design criteria, and special treatments of individual SSCs. The design process of each SSC subsequently follows largely prescriptive design code provisions that are developed based on target risk and performance goals. As the design of individual SSCs matures, it feeds back into the probabilistic safety assessment. The process typically iterates until the SSC designs and risk outcomes converge.

One main interface between the risk metrics from the probabilistic safety analysis and the prescriptive design process is the selection of the design-basis hazard level. NEI 18-04 (2018) provides preliminary guidance on this topic, stating that this hazard can be selected using one of multiple approaches, deterministic or probabilistic. Experience with nuclear reactor developers and industry practitioners indicates that this topic is open to several interpretations and practices, which introduces a source of uncertainty in the design process workflow. This paper attempts to outline a framework for the selection of a design basis hazard level that is consistent with both probabilistic risk targets and deterministic provisions of RIPB design codes and standards. This paper develops and demonstrates the design basis level determination process using seismic hazard, but the approach is hazard-agnostic and can be readily generalized to other hazards.

SEISMIC MARGIN-BASED PERFORMANCE ASSESSMENT

IAEA TE-2043 developed a technique to determine the seismic margin required to achieve a target annual frequency of unacceptable performance. This guidance was meant to be applied to a situation where (1) a nuclear installation or a design of it exists, (2) the nuclear installation has a design-basis earthquake (DBE) hazard level, (3) the seismic design of SSCs follows various codes and standards that may or may not have explicit reliability margins, (4) a safety assessment of the installation is performed using the seismic margin or PSA-based seismic margin methods to identify the installation-level HCLPF capacity in terms of ground motion intensity,[1] and (5) the nuclear installation has a target performance goal (TPG) defined as an annual frequency of unacceptable performance, $\lambda_{f,T}$.

IAEA TE-2043 used the closed-form risk integral equation developed by Kennedy and Short (1994) to develop an approach for identifying the minimum seismic margin relative to the DBE that guarantees achieving the TPG. Kennedy and Short (1994) showed that the risk convolution integral can be quantified using Eqn. 2 for a lognormal fragility functions and typical hazard curve shapes represented by the power law in Eqn. 1:

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

where:

$H(a)$	is the mean annual frequency of ground motion intensity exceedance (MAFE)
a	is the value of the ground motion intensity parameter (e.g., PGA)
K_1	is the constant that anchors the hazard curve and is equal to $H(A_{DBE}) \times (A_{DBE})^{KH}$
K_H	is the slope of the hazard curve in log-log space and is equal to $=1 / \log_{10}(A_R)$

[1] Without loss of generality, the peak ground acceleration (PGA) will be considered to be the ground motion intensity measure in this paper for simplicity.

A_{DBE} is the design-basis PGA
A_R is the increase in PGA across one MAFE decade

the risk convolution integral can be quantified as:

$$\lambda_f = K_1 \ (A_m)^{-K_H} \ e^{0.5\,(K_H\,\beta)^2} \tag{2}$$

where:

λ_f is the mean annual frequency of failure (e.g., core damage for a nuclear power plant)
A_m is the median capacity
β is the logarithmic standard deviation (combined for randomness and uncertainty)

Equation 2 can be written in terms of the HCLPF capacity as:

$$\lambda_f = K_1 \ (A_{HCLPF} e^{2.33\beta})^{-K_H} \ e^{0.5\,(K_H\,\beta)^2} \tag{3}$$

Equation 3 can be simplified into:

$$\lambda_f = H(A_{HCLPF}) \ F(A_R) \tag{4}$$

$$F(A_R) = \frac{e^{0.5\,(K_H\beta)^2}}{e^{2.33\,\beta K_H}} \tag{5}$$

where $F(A_R)$ represents the sensitivity of the mean annual performance metric to the site hazard and fragility parameters for plants whose HCLPF capacities all correspond to the same hazard level, $H(A_{HCLPF})$. Figure 1 shows a plot of this sensitivity (reproduced from IAEA TE-2043).

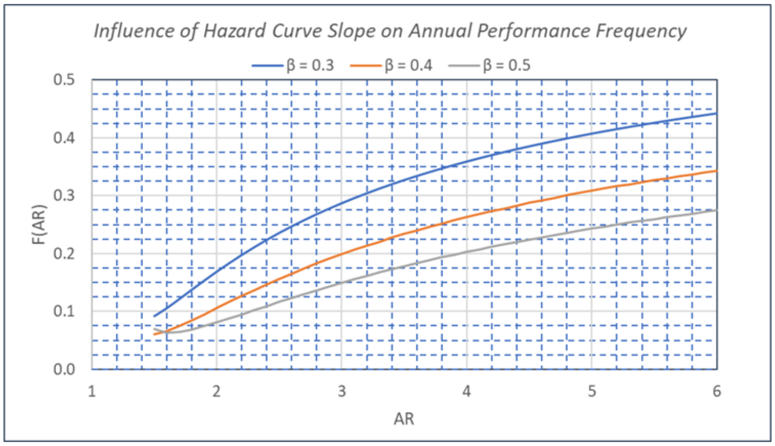

Figure 1 Sensitivity of annual performance to site and fragility parameters given $H(A_{HCLPF})$.

Figure 1 suggests that, for a given site and plant design, i.e., A_R and $H(A_{HCLPF})$, the mean annual frequency of failure increases when the variability due to uncertainty and randomness decreases. That is, when the design has less reserve between the high confidence and the median PGA at failure. Figure 1 also indicates that, within the typical A_R range of 2-4, the factor $F(A_R)$ nearly doubles for all β cases.

IAEA TE-2043 derived the following expression for the margin or ratio R required between the HCLPF and the DBE PGAs to achieve an annual TPG, referred to by $\lambda_{f,T}$:

$$R = [R_{DP}\, F(A_R)]^{\frac{1}{K_H}} \tag{6}$$

$$R_{DP} = \frac{H(A_{DBE})}{\lambda_{f,T}} \tag{7}$$

Note that R_{DP} is the ratio between the annual frequencies of the DBE hazard level and the TPG. Figure 2 shows the relationship between the minimum recommended margin and the site hazards slope parameter for (reproduced from IAEA TE-2043).

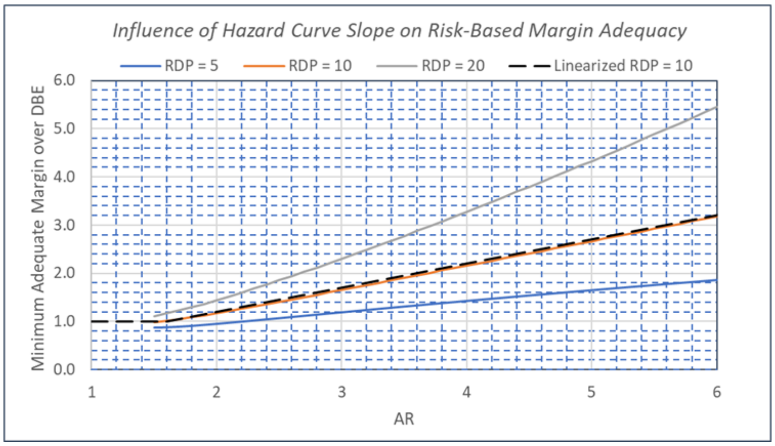

Figure 2. Minimum recommended margin between HCLPF and DBE to achieve TPG for β = 0.3.

Finally, to protect against the undesirable installation design situations that may result in unusually low uncertainty in the seismic capacity and an abrupt increase in the plant-level fragility (PLF) function due to a small increase in the PGA, or so-called cliff-edge effects, IAEA TE-2043 recommended that the ratio of the 10% point on the PLF to the DBE be at least equal to 1.4R, i.e., that the conditional probability of failure at 1.4R×DBE be ≤ 10%.

LEVERAGING MARGINS-BASED PERFORMANCE ASSESSMENT FOR SSC RIPB DESIGN

Seismic design codes and standards are increasingly becoming performance based. For example, the seismic design provisions in ASCE/SEI 41 (2023 and some earlier revisions) and ASCE/SEI 43 (both the 2005 and 2019 revisions) are explicitly performance based. The provisions for seismic design and those for several other hazards in ASCE/SEI 7-22 (2022) and some earlier revisions are currently performance based. Performance in the context of these design standards is defined on an SSC-by-SSC basis, unlike performance defined in IAEA TE-2043 as fulfilling the safety functions of an entire nuclear installation. The seismic margin referred to in TE-2043 is computed for the entire facility or for an accident sequence using the SMA or PSA-based SMA methodology.

The concepts and formulations developed in TE-2043 are, however, readily adaptable to RIPB selection of seismic design basis of individual SSCs. In the context of RIPB seismic design for individual SSCs, the objective is selecting a DBE that results in the annual frequency TPG for unacceptable performance of the SSC being met when the performance-based design of the SSC satisfies the target reliability levels of the applicable design code.

The following process is proposed to develop an RIPB DBE hazard level for individual SSCs that have a defined TPG, using primarily Equation 6.

1. Determine the annual frequency that defines the TPG of the SSC.
2. Identify the site hazard slope parameters A_R for the spectral accelerations used to define the DBE ground spectrum within the spectral frequency range of interest.
3. Identify the RIPB design standard target conditional failure probability at the DBE, $P_{f|DBE}$. The conditional failure probability represents a scenario-based performance target (for the DBE scenario).
4. If this conditional probability is equal to 1%, i.e., the same as HCLPF, set the target R in Equation 6 to 1.0.
5. If this conditional probability is not equal to 1%, set the target R in Equation 6 to:

$$R = \quad e^{[\Phi^{-1}(P_{f|DBE}) - \Phi^{-1}(0.01)]\beta} \tag{8}$$

6. Find the value of R_{DP} that satisfies Equation 6. Note that this value will increase with R.
7. Determine the DBE hazard level, $H(A_{DBE})$ at each spectral frequency by rearranging Equation 7.
8. Compute the corresponding spectral accelerations to develop the DBE ground motion spectrum.

The process steps outlined above may not always conveniently fit the existing workflow of several RIPB codes and standards. For example, ASCE/SEI 43-19 (2019) determines the DBE based on a factor multiplied by a "reference" ground motion uniform hazard response spectrum (UHRS) that corresponds to a MAFE equal the TPG. Similarly, ASCE/SEI 43-05 (2005), which still constitutes the design basis for many nuclear structures, determined the DBE based on a factor multiplied by a reference ground motion UHRS that corresponds to a MAFE equal to 10×TPG. Equation 10 uses the parameter A_{Ref} to refer to the spectra ordinates of either reference ground spectrum, as applicable. The steps outlined above can be modified as follows to achieve a more streamlined and transparent workflow for these standards.

1. Repeat Steps 1 to 3.
2. Set R_{DP} in Equation 6 to the ratio between the MAFE of the reference spectrum, $H(A_{Ref})$, and the TPG annual frequency, $\lambda_{f,T}$.
3. Compute R following Equation 6.
4. Compute an RIPB factor specific to the design code performance target. This factor is equal to R if $P_{f|DBE}$ targeted by the design code is 1% and is generally equal to:

$$R_{RIPB} = Re^{[\Phi^{-1}(P_{f|DBE}) - \Phi^{-1}(0.01)]\beta} \tag{9}$$

5. Compute the DBE ground spectrum by scaling the reference ground spectrum:

$$A_{DBE} = R_{RIPB} \times A_{Ref} \tag{10}$$

EXAMPLE APPLICATIONS TO RIPB DESIGN STANDARDS

Application to ASCE/SEI 43-19

The ASCE/SEI 43-19 process for establishing the DBE ground motion proceeds as follows:

1. Define a seismic design category (SDC) for each SSC. Each SDC has an established target annual frequency of failure TPG, $\lambda_{f,T}$.

2. Define the limit-state of interest to the design (for example, limited inelastic deformation).
3. Compute the ground motion UHRS at an MAFE equal to the TPG, which corresponds to A_{Ref} above. This means that the ratio R_{DP} = 1.0 (Equation 7).
4. Set scenario-based performance targets to $P_{f|DBE}$ = 1% and $P_{f|1.5DBE}$ = 10% (or lower). The philosophy in setting these two targets is consistent with the cliff-edge avoidance recommendation in IAEA TE-2043.
5. Compute a scale factor (SF) based on the slope of the hazard curve, A_R, with an assumed β and imposed lower-bound constraints.
6. Calculate the DBE similar to Equation 10 but using SF instead of R_{RIPB}.

The process introduced in this paper is readily appliable to ASCE/SEI 43-19. Following the streamlined workflow steps outlined in the previous section, the factor, R_{RIPB} is computed for a range of hazard curve and fragility function slopes. Figure 3 shows the results of these computations. This factor is analogous to the scale factor SF in ASCE/SEI 43-19 but explicitly reflects the sensitivity to β and excludes the lower-bound constraints.

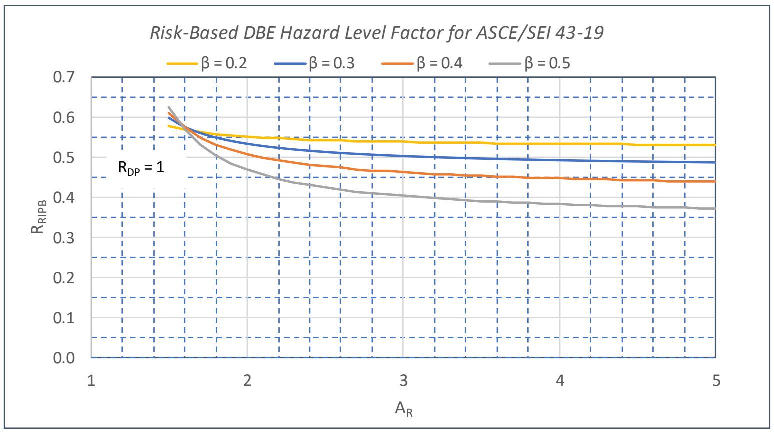

Figure 3. RIPB DBE factor illustration for ASCE/SEI 43-19 performance goals.

For $\beta \geq 0.39$, the condition $P_{f|DBE}$ = 1% governs the performance target. Equation 9 is used with $P_{f,DBE}$ = 1% to compute R_{RIPB} . For lower values, the condition $P_{f|1.5DBE}$ = 10% governs the performance target. Equation 9 is used with $P_{f|1.5DBE}$ = 10% to compute a factor analogous to R_{RIPB} that corresponds to $A_{1.5DBE}$, and that factor is then divided by 1.5 to compute R_{RIPB} for A_{DBE}.

The following observations are made:

- The computed values for R_{RIPB} are consistent with the corresponding tabulated values of SF in Table C2-4 of ASCE/SEI 43-19. This confirms that they can be used to develop similar factors for arbitrary site, fragility parameters, and RIPB design code performance target.
- The DBE factor R_{RIPB} for ASCE/SEI 43-19 is relatively insensitive to the slope of the hazard curve after A_R exceeds about 2.5. Its sensitivity is notable for steeper hazard curves (A_R < 2.5) and flat fragility curves (i.e., as β increases). This insensitivity is desirable for design process stability.
- The DBE factor R_{RIPB} for ASCE/SEI 43-19 decreases gradually as β increases (except at unrealistically steep hazard curves with A_R < 1.6). A practical design decision may be to select a representative R_{RIPB} for the site based on a reasonably low estimate of β for the SSCs to be designed.

Application to ASCE/SEI 43-05

The ASCE/SEI 43-05 process for establishing the DBE ground motion is similar to that of ASCE/SEI 43-19, except for the following details.

1. The ground motion UHRS that corresponds to A_{Ref} is equal to 10×TPG. This means that the ratio R_{DP} = 10 (Equation 7).
2. Instead of the scale factor, SF, calculate a design factor (DF), also based on the slope of the hazard curve, A_R, with an assumed β and imposed upper-bound constraints.
3. Calculate the DBE similar to Equation 10 but using DF instead of R_{RIPB}.

Similar to ASCE/SEI 43-19, the process introduced in this paper is readily appliable to ASCE/SEI 43-05. R_{RIPB} is computed as discussed in the previous sub-section, but with R_{DP} = 10. Figure 4 shows the results of these computations. This factor is analogous to the design factor DF in ASCE/SEI 43-05 but explicitly reflects the sensitivity to β and excludes the upper-bound constraints. The following observations are made:

- The DBE factor R_{RIPB} for ASCE/SEI 43-05 is higher than unity, compared to that for ASCE/SEI 43-19. This is common knowledge since the reference ground motion UHRS in ASCE/SEI 43-19 corresponds to the TPG while that in ASCESEI 43-05 corresponds to the 10×TPG and has a lower intensity.
- The DBE factor R_{RIPB} for ASCE/SEI 43-05 is sensitive to the slope of the hazard curve for all values of A_R. This sensitivity slightly increases for steeper fragility curves (i.e., as β decreases).
- The DBE factor R_{RIPB} for ASCE/SEI 43-05 decreases gradually as β increase.

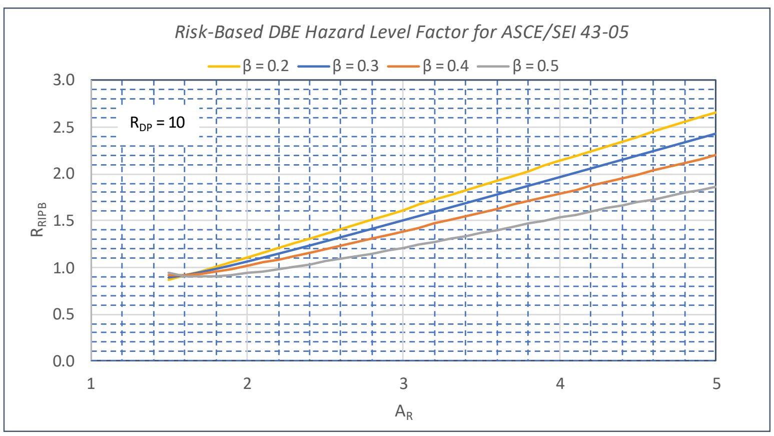

Figure 4. RIPB DBE factor illustration for ASCE/SEI 43-05 performance goals.

Application to ASCE/SEI 7-22

The ASCE/SEI 7-22 (2022) process for establishing the DBE ground motion is written in procedural steps intended for prescriptive implementation by design engineers, which is too protracted to effectively reproduce here. The relevant elements of this process for building structures and underlying technical basis are as follows:

1. Define a seismic risk category and corresponding importance factor from 1.0 to 1.5.
2. Starting with an idealized UHRS shape anchored to spectral accelerations that have an MAFE of 4E-4/yr:

a. For Risk Category I, the TPG annual frequency, $\lambda_{f,T}$, is 1% in 50 years for structure collapse, i.e., approximately 2E-4/yr.
b. Based on the hazard curve slope, find a risk-targeted adjustment factor to scale the 4E-4/yr UHRS to achieve the TPG. This factor may be found by iteration or taken from pre-computed values.
c. Multiply the adjusted UHRS by a factor to convert it to a maximum-direction ground motion if applicable. The result is the risk-targeted maximum considered earthquake, $MRE_{R.}$
d. Compare the MCE_R spectrum to the deterministic cap adopted in ASCE/SEI 7-22 and set MRE_R to the lesser spectrum.
e. The DBE spectrum is two-thirds of the MCE_R.

3. Assuming a β of 0.6, the code design provisions (i.e., load combinations, factors of safety) at the DBE target a conditional probability of collapse of 10% at the MCE_R, i.e., $P_{f|1.5DBE} = 10\%$.
4. Assuming a β of 0.6, applying the code provisions at the DBE target a conditional probability of failure for ordinary non-critical structural members of 25% at the MCE_R. There is no annual frequency TPG specified for this damage state, so this example application focuses on collapse.
5. For other risk categories, the DBE demands are scaled by the importance factor. Assuming a β of 0.6 results in target conditional probabilities of failure at the MCE_R identified in Section 1.3.1.3 of ASCE/SEI 7-22.

The process introduced in this paper is appliable to ASCE/SEI 7-22, as summarized in Table 1. The factor R_{RIPB} for the ASCE/SEI 7-22 performance-based provision is directly proportional to the maximum-direction ground motion multiplier, $R_{RotD100}$.

Table 1: DBE factor computation for ASCE/SEI 7-22 performance goals.

Parameter	Value	Basis	Comments
A_{Ref}	4E-4/yr	ASCE 7-22	
$\lambda_{f,T}$	2E-4 / yr	ASCE 7-22	
R_{DP}	2.0	Eqn. 7	
$P_{f\|1.5DBE}$	10%	ASCE 7-22	
$R_{RIPB,1.5DBE}$	$2\ F(A_R)]^{\frac{1}{K_H}} e^{1.045\beta}$	Eqn. 9	This R_{RIPB} factor corresponds to 1.5DBE
R_{RIPB}	$\frac{2}{3} R_{RIPB,1.5DBE} R_{RotD100}$	ASCE 7-22	$R_{RotD100}$ is the conversion factor for maximum-direction ground motion.

Figure 5 shows the computed ratios of R_{RIPB} to $R_{RotD100}$ for a range of site hazard and fragility slope parameters. The following observations are made assuming a maximum-direction ground motion factor $R_{RotD100}$ = 1.0 (scale the R_{RIPB} values listed below by $R_{RotD100}$ as applicable):

- The DBE factor R_{RIPB} for ASCE/SEI 7-22 is lower than unity.
- For typical sites, with A_R between 2 and 4 in the DBE hazard range, the DBE factor R_{RIPB} for ASCE/SEI 7-22 is between about 0.6 and 0.8.
- Considering that β for collapse of commercial construction is likely large, the practical range of R_{RIPB} for ASCE/SEI 7-22 is between about 0.6 and 0.7 and shows little sensitivity to A_R. This narrow range is desirable for design process stability.

- For A_R < 1.8, the DBE factor R_{RIPB} for ASCE/SEI 7-22 shows significant sensitivity to A_R and β, and approaches becoming mathematically unstable as β decreases. However, hazard curve slopes this steep not realistic at 4E-4/yr MAFEs.

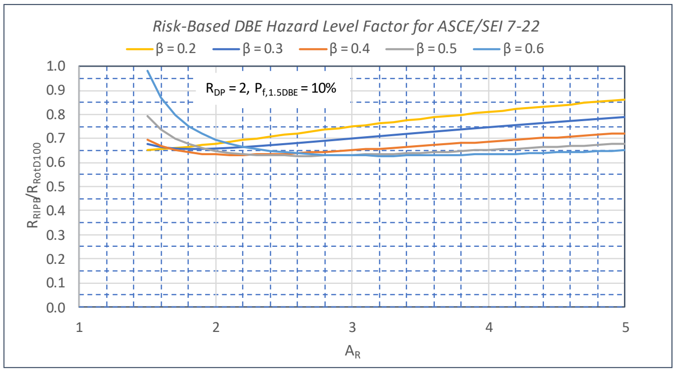

Figure 5. RIPB DBE factor illustration for ASCE/SEI 7-22 performance goals.

CONCLUSION

This paper presented a process to identify a seismic DBE hazard level for RIPB design codes and standards. The process depends on the annual frequency TPG and the target conditional probability(ies) of failure at the DBE (or multiples of the DBE) specified by the design code or standard. It leverages the performance-based nuclear installations seismic margins adequacy assessment process developed in IAEA TE-2043 and repurposes them to inform the design bass of individual SSCs. The process implementation procedure is efficient and versatile to accommodate various workflows of RIPB design codes and standards. Most commonly, implementation is executed by computing an RIPB DBE factor that gets multiplied by a reference ground spectrum to determine the DBE ground spectrum. The reference ground spectrum is established in the applicable design code or standard. Several illustration examples demonstrate that this process is applicable to several common RIPB seismic design standards published by ASCE, and represents a generalized approach that can be customized for the particular provisions of each standard. The example application results for each standard revealed insights into the sensitivity to site hazard and fragility curve slopes and observations on the provisions of each standard from a design process stability perspective. The mathematical basis of the process is hazard-agnostic and sufficiently general to be applied to determining RIPB design basis levels of hazards other than earthquakes, using the hazard curve and fragility information and any particular considerations applicable to each hazard.

ACKNOWLEDGEMENTS

The development of this paper and IAEA TE-2043 owe intellectual homage to the pioneering work and many years of interactions and generous mentorship by the late Dr. Robert P. Kennedy. The first author wishes to thank Prof. Andrew S. Whittaker and Drs. Brian McDonald and Sai Sharath Parsi for sharing ideas, discussions, and in-progress technical material that informed and improved the focus of this paper.

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