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EXPLICIT INCORPORATION OF UNCERTAINTIES IN DETERMINATION OF SAFE SHUTDOWN EARTHQUAKE FOR NUCLEAR FACILITIES

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ABSTRACT

The current approach for determination of the safe shutdown earthquake (SSE) for nuclear facilities is not sensitive to the uncertainties involved in obtaining the hazard and fragility curves. This creates several potential pitfalls, the most important of which is a disincentive for more thorough site investigation and more accurate evaluation of the structures, systems, and components (SSCs). We briefly describe the current approach which is based on the mean annual probability of failure (performance target) and highlight the potential problems using realistic examples. We pose the question whether there should be an explicit incentive built in the design and analysis codes to reduce epistemic uncertainties, and reason that the answer is affirmative. We propose an improved uncertainty sensitive formulation based on a higher percentile of the annual probability of failure (e.g. 84th percentile) and provide the formulation for its rigorous application as well as a simplified version suitable for adoption in design codes. Finally, we demonstrate that the proposed formulation is equivalent to the current approach for a site with "reasonable" epistemic uncertainty and that for the same performance criterion, the SSE would decrease with reducing epistemic uncertainty and increase when excessive epistemic uncertainty is present. In other words, "knowledge" is rewarded and lack-thereof is penalized.

INTRODUCTION

The current approach for determination of the safe shutdown earthquake (SSE) for nuclear facilities is described in ASCE 43-05 and ASCE 43-18 (under committee review). As specified in these documents, the SSE which is taken as the design basis earthquake (DBE) and defined in terms of a design response spectrum (DRS) for new facilities, is determined using performance-based objectives that are defined by a target performance goal (i.e. mean annual probability of unacceptable performance) and mean conditional probabilities of unacceptable performance.

The target performance goal (P_{TF}) is specified in ASCE 43 for different seismic design categories (SDC, per ANS 2.26). For example, for SDC 5, which applies to safety related nuclear systems, structures, and components (SSCs), $P_{TF} = 1 \times 10^{-5}$ is specified. The conditional probabilities of unacceptable performance define the criteria that are expected to be met if the SSCs are designed for demands based on the DRS (i.e. conditioned on DRS) and capacities as specified in ASCE 43 and related standards. The DRS is formulated to achieve both (1) less than about a 1% [mean] probability of unacceptable performance given the DBE ground motion and (2) less than about a 10% probability of unacceptable performance given 1.5 times the DBE ground motion. These two criteria define two points on the expected minimum mean fragility curve for the SSC.

The derivation of the DRS to meet the abovementioned performance target is described in the commentary of the ASCE 43 with more details provided in Kennedy (2011). The latter raises the following four issues that need to be established for determination of a risk consistent DRS:

1. What is the target seismic risk [performance] goal (P_{TF}) that is to be aimed at by the specified seismic criteria? Kennedy (2011) reasons that the first onset of significant inelastic deformation (FOSID) is a conservatively biased indicator for the core damage frequency (CDF) and provides justification that the CDF is about an order of magnitude less than the P_{TF} defined based on FOSID.

2. What is the level of conservatism implied by use of the specified seismic design criteria? It is expected that following the specifications and requirements of the code, there is sufficient conservatism such that both of the goals for conditional probabilities of unacceptable performance (i.e. less than 1% probability due to DRS and less than 10% probability due to 1.5 × DRS) are met. The seismic margin factor (F) is defined as the ratio of the ground motion at the onset of failure to DRS and it is widely assumed that the pth percentile of F (denoted as F_p) associated with a conditional probability of failure (p) follows a lognormal distribution and is completely described by any fractile of the seismic margin factor (e.g. $F_{50\%}$ for median or $F_{1\%}$) and the logarithmic standard deviation (β). Thus, the above-mentioned criteria would require that $F_{1\%} > 1.0$ and $F_{10\%} > 1.5$.

3. What is the reference hazard exceedance frequency (H) where the reference uniform hazard response spectrum (UHRS) is defined? A risk-consistent DRS is calculated by multiplying a UHRS at a given hazard level H by a design factor (DF, ASCE 43-05) or scale factor (SF, ASCE 43-18). The hazard level (H) is recommended to be within 1 to 20 times P_{TF}. The value of the target hazard level is specified in ASCE 43. For example, for SDC 5, ASCE 43-05 specified $H = 10^{-4}$ (to be multiplied by a DF which is larger than 1.0), and ASCE 43-18 specifies $H = 10^{-5}$ (to be multiplied by a SF which is smaller than 1.0). Note that the two approaches are essentially equivalent, although the ASCE 43-18 approach provides more transparency and consistency.

4. What is the design factor (DF, ASCE 43-05) or scale factor (SF, ASCE 43-18) that needs to be applied to the reference UHRS to determine the risk consistent DRS? The derivation of the DF is described in detail in Kennedy (2011) and is repeated in the text below for completeness and generalization. Note that the SF of ASCE 43-18 is obtained as DF/AR, where AR is the slope of the hazard curve in the vicinity of P_{TF} as more formally defined later.

We closely follow the approach described in Kennedy (2011) with the exception that we base our formulation on a higher percentile of the annual probability of failure (e.g. 84th percentile). We calibrate the formulation such that for a "well-investigated" site with reasonable epistemic uncertainties for hazard and fragility curves, the calculated DRS would remain unchanged from the current ASCE 43 approach. The SSE would increase with increasing epistemic uncertainties and decrease with a reduction in the epistemic uncertainties. In our suggested formulation, we need to establish the following two additional issues:

5. What is reasonable sensitivity to the uncertainties involved in the determination of P_{TF} to be included in the DRS formulation? The sensitivity of the DRS can be calibrated using a reference fractile of P_{TF} to be considered for the risk evaluation. The higher the fractile considered, the more sensitive the final DRS becomes to the uncertainties involved.

6. What level of epistemic uncertainty is considered "reasonable" for a facility? The uncertainties of the P_{TF} can be characterized by its logarithmic standard deviation (β_{PF}) which as we will show is a function of hazard uncertainty (β_H), slope of the hazard curves, and fragility epistemic uncertainties (β_u). We suggest using benchmark epistemic uncertainties that are consistent with results previously obtained for well-investigated sites, structures, systems, and components.

PROBLEM STATEMENT

This paper is aimed at addressing the following challenges:

1. The standard-of-good-practice in site investigation, seismic hazard analysis, structural modelling, and risk evaluation encompasses a wide range of acceptable approaches which are conceptually sound but not equivalent in terms of their outcomes. Generally, some would say ideally, more accuracy and higher confidence (i.e. lower epistemic - knowledge based - uncertainty) is gained by using more thorough investigative studies and analytical methods which require more effort. Moreover, contrary to common perception, the cruder approaches do not necessarily produce results that are more conservative (examples are approach 2A of NUREG 6728 (McGuire, et al. (2001)) in site response analysis and lumped-mass and stick models of ASCE 4-16). The mean-based definition of the performance goal and corresponding formulation to obtain the DRS representing the SSE ground motion does not include an explicit incentive for use of *better* methods and reduction of epistemic uncertainties. In fact, it is possible and not uncommon to have cases where using less accurate methodologies and increasing the epistemic uncertainties would lead to a reduction in the DRS; thus creating an irrational disincentive for use of more accurate investigative and analytical methods.

2. Uncertainties involved in determination of the annual probability of failure are large. The uncertainty in determination of the annual probability of failure strongly depends on the uncertainties in the hazard curves, fragility curves, and the slope of the hazard curves in the vicinity of the target performance probability. The logarithmic standard deviation of the fragility curve (referred to as β) is typically in the range of 0.3 to 0.6. The uncertainty of the hazard curves (i.e. the uncertainty in the amplitude of the pseudo spectral accelerations at a given probability of exceedance) are typically in the range of 0.4 to 0.7. For a typical Central and Eastern United States (CEUS) hazard curve, the β value for the annual probability of failure is in the range of 1.0 to 1.5 resulting in a factor of 2.7 to 4.5 difference between the 84^{th} and median of the annual probability of failure. Because any considerations of the uncertainties involved are currently implicit, this large level of uncertainty is often not known and not appreciated in the practicing community of engineers.

3. In recent years, significant advances have been made in the fields of seismology and earthquake engineering. Better frameworks for characterizing seismic sources, more sophisticated models for ground motion prediction, and more accurate analytical models for geotechnical and structural evaluations are being used. While these advances have helped us better understand and reduce the epistemic uncertainties involved, they do not necessarily result in a reduction in mean estimates of the ground motions and seismic demands. Because the mean ground motion indicators and mean seismic responses are often used as the basis for design, there has been many cases where successive updates to the code and updates to analytical methods have caused appreciable increases rendering the designs of the recent past obsolete. This leads to an unfair presumption of a fundamental flaw in the previous methodology as opposed to the natural state of gradual evolution of our state-of-knowledge which is better explained by explicit inclusion and discussion of epistemic uncertainties.

Current design codes have a rational goal of reducing the risk of undesirable performance. The performance-based approaches specified in design and analysis codes (such as ASCE 43 and ASCE 4) aim to limit the risk to a prescribed target mean annual probability of failure. It follows that obtaining reasonable accuracy in estimating the said annual probability of failure should also be a goal of the governing design and analysis codes. Therefore, we argue that the design and analysis codes should more actively promote reduction of uncertainties in addition to the reduction of the mean estimate of the annual probability of failure to achieve the desired risk with reasonable confidence.

The current limits for the mean probability of failure were chosen very conservatively because the large uncertainty in the estimation of the annual probability of failure was inherently understood. We argue that if more accurate methods of estimating risk are used and the mean annual probability of failure can be estimated with higher confidence (less uncertainty), a less stringent (higher) threshold for the mean risk can be permitted. Conversely, where the methods used lead to high uncertainty in estimation of the annual probability of failure, a more conservative (lower) threshold for the mean risk should be enforced. As demonstrated below, the current simplified formulation of ASCE 43 is not in-fact risk-consistent and generally results in an undesired trend as described above, but without making the benefits of having less uncertainty explicit.

FORMULATION

Mean-Based Risk-Consistent Formulation

The mean-based risk-consistent formulation is described in detail in Kennedy (2011). We provide a summary of this formulation, for completion, with slight change in emphasis.

The annual probability of failure (PF) is obtained from equation (1) by integrating the increment of conditional probability of failure given a (i.e. increment of the fragility curve, $\frac{dP_F(a)}{da}$) times the probability of ground motion exceeding a (i.e. the hazard curve, $H(a)$), or equivalently the conditional probability of failure given a (i.e fragility curve, $P_F(a)$) times the incremental probability of ground motion having value of a (i.e. increment of the hazard curve, $\frac{dH(a)}{da}$). If the mean fragility and mean hazard curves are used, the mean annual probability of failure is obtained from this equation.

$$PF = \int_0^\infty \frac{dP_F(a)}{da}\, H(a)\, da = -\int_0^\infty P_F(a)\, \frac{dH(a)}{da}\, da \tag{1}$$

The above equation is simplified by making two assumptions: (A) assuming that the hazard curve is linear in log-log space in the vicinity of the PF with the slope of K_H and constant value of $\log(K_1)$, as described by equation (2); and (B) assuming that the fragility curve follows a log-normal distribution with logarithmic standard deviation of β and median fragility capacity of $C_{50\%}$. These assumptions simplify the calculation of PF as shown in Equation (3).

$$log\big(H(a)\big) = -K_H \times log(a) + log(K_1) \Rightarrow H(a) = K_1 a^{-K_H} \tag{2}$$

$$PF = \int_0^\infty \frac{dP_F(a)}{da}\, H(a)\, da = \int_0^\infty \frac{1}{\sqrt{2\pi}\beta a} e^{-\frac{\left(ln(a)-ln(C_{50\%})\right)^2}{2\beta^2}} K_1 a^{-K_H}\, da = K_1 e^{-K_H\, ln(C_{50\%}) + \frac{1}{2}(K_H\beta)^2} \tag{3}$$

Defining a reference hazard level (H) roughly in the same order of magnitude as the target PF and its corresponding ground motion level, C_H, the constant (K_1) is obtained from equation (2) as $K_1 = HC_H^{K_H}$. Substituting this value in equation (3) and denoting $\alpha = \frac{1}{2}(K_H\beta)^2$, equation (3) is simplified as shown in equation (4), where $F_{50\%} = C_{50\%}/C_H$ is the median seismic margin factor.

$$PF = He^{\alpha}F_{50\%}^{-K_H} \tag{4}$$

The DRS is calculated by applying a factor to the ground motion at the reference hazard level (C_H) as shown in equation (5). This equation uses a design factor (DF) consistent with ASCE 43-05 formulation. Equivalently, a scale factor (SF, ASCE 43-180) can be used which is related to the DF by the equation $SF = DF/AR$, where AR relates to the slope of the hazard curve as $K_H = 1/\log(AR)$. In this discussion, we'll go through the derivation of DF but note that the derivation of SF equivalently follows.

$$DRS = C_H \times DF \tag{5}$$

As discussed before, the target levels of conservatism specified by ASCE 43 are described by the $F_{1\%} > 1.0$ and $F_{10\%} > 1.5$ limits. As shown in equation (6), the p^{th} percentile of the seismic margin factor is obtained as the ratio of the p^{th} percentile of the fragility capacity (C_p) to the DRS. Combining this equation with equations (4) and (5) and using the lognormal distribution for the fragility capacity yields the equation for DF (equation (7)), where X_p is the standard normal variable for p^{th} percentile, $R_p = H/P_{TF}$ (consistent with ASCE 43 formulation), and $f = -\alpha - K_H X_p \beta$. Note that the β in this equation defines the uncertainty of the fragility [capacity] function (same as the uncertainty of the seismic margin factor, F_p) used. Therefore, it refers to the composite uncertainty, β_c, if a mean fragility curve is utilized.

$$F_p = C_p/C_H \tag{6}$$

$$DF = \left(R_p e^{-f}\right)^{\frac{1}{K_H}}/F_p \tag{7}$$

Except for the uncertainty (β), all parameters involved in the definition of DF can be known a priori: mean H and mean P_{TF} are specified, K_H is known from the hazard curve, and limits on F_p are established for 1 and 10 percentiles. Therefore, the DF is established using a reasonable range for β, typically between 0.3 and 0.6 for composite uncertainty.

Uncertainty-Sensitive Risk-Consistent Formulation

The mean-based formulation above is modified with the goal of introducing appropriate uncertainty of the PF in the formulation of the DF. As discussed before, a rational way to achieve this goal is to rewrite the formulation in terms of a higher fractile for the target probability of failure, P_{TF}, say P_{TF_q}, where q is the selected fractile which is described using equation (8) assuming a lognormal distribution for P_{TF}. In this equation, $P_{TF_{50\%}}$ refers to the median target probability of failure, $\beta_{P_{TF}}$ refers to the uncertainty associated with the P_{TF}, and X_q refers to the variable for the standard normal distribution associated with q^{th} percentile.

$$P_{TF_q} = P_{TF_{50\%}}\, e^{\beta_{P_{TF}} X_q} \tag{8}$$

When the target PF is achieved at the q^{th} percentile, i.e. $PF_q = P_{TF_q}$, the median probability of failure ($PF_{50\%}$) is described by equation (9), where β_{PF} describes the realized uncertainty in the estimation of PF, and $\Delta\beta_{PF} = \beta_{P_{TF}} - \beta_{PF}$ is the difference between the realized uncertainty in PF, which is dependent on the *quality* of information in the supporting analysis, and the *target* uncertainty for annual probability of failure.

$$PF_{50\%} = P_{TF_{50\%}}\, e^{(\beta_{P_{TF}}-\beta_{PF})X_q} = P_{TF_{50\%}}\, e^{\Delta\beta_{PF} X_q} \tag{9}$$

Assuming that the realized uncertainty for PF and P_{TF} have the same order of magnitude, thus the ratios between median and mean probabilities are roughly the same, the above equation can also be used for the mean probabilities as shown in (10), where PF and P_{TF} refer to the mean probability of failure and mean target probability of failure, respectively.

$$PF = P_{TF} e^{(\beta_{P_{TF}}-\beta_{PF})X_q} = P_{TF} e^{\Delta\beta_{PF} X_q} \tag{10}$$

Consistent with the ASCE 43 definition for $R_p = H/P_{TF}$, this parameter is redefined as R_p^* using the uncertainty-sensitive formulation here as shown in equation (11), and substituted R_p in equation (7) to yield the updated formulation for DF, denoted as DF^* as shown in equation (12).

$$R_p^* = \frac{H}{PF} = \frac{H}{P_{TF}} e^{-\Delta\beta_{PF} X_q} = R_p e^{-\Delta\beta_{PF} X_q} \tag{11}$$

$$DF^* = \frac{\left(R_p^* e^{-f}\right)^{\frac{1}{K_H}}}{F_p} = DF\ e^{-\frac{\Delta\beta_{PF}}{K_H} X_q} \tag{12}$$

Similar to the definition of DF, with the exception of the β_{PF}, and β, all parameters involved in the calculation of DF^* are known a priory; they include the target uncertainty of the annual probability of failure ($\beta_{P_{TF}}$), in addition to those discussed for DF. Note that $\beta_{P_{TF}}$ can either be directly specified in the governing code of reference or its effect can be indirectly incorporated as discussed below.

The uncertainty of the estimated annual probability of failure (β_{PF}) can be derived from equation (1) or its estimated version, equation (4), if the distribution of hazard and fragility curves are known. The assumption that the fragility curves follow a lognormal distribution is widely adopted and generally accepted. The distribution of the hazard curve, however, would depend on the underlying seismic hazard parameters and is generally not lognormal. As a practical matter for the estimation of β_{PF}, we assume that both fragility and hazard curves are lognormally distributed. With this assumption and starting from equation (4), the β_{PF} is obtained as shown in equation (13), where β_H refers to the uncertainty of the hazard curve and $\beta_{F50\%}$ refers to the uncertainty of the median seismic margin factor. Recognizing that the uncertainty in the median seismic margin factor is the same as the uncertainty in the median fragility capacity or the epistemic uncertainty of the fragility curve (β_u), the second equality in equation (13) is established.

$$\beta_{PF}^2 = \beta_H^2 + K_H^2\,\beta_{F_{50\%}}^2 = \beta_H^2 + K_H^2\,\beta_u^2 \tag{13}$$

Note that in practice, where the hazard curves and the annual probability of failure are generally not lognormally distributed, loosely defined β_H and β_{PF} as the average differences between the 84th and median and median and 16th percentiles of their respective quantities in the logarithmic space, can be used along with equation (13).

The value of β_{PF} estimated from equation (13) can be used to calculate $\Delta\beta_{PF}$ in equation (12) if $\beta_{P_{TF}}$ is directly specified. Alternatively, and preferably from the stand point of code implementation as will be discussed later, equation (13) can be used to derive an equation for $\Delta\beta_{PF}$ in terms of $\Delta\beta_H = \beta_{H_T} - \beta_H$ and $\Delta\beta_u = \beta_{u_T} - \beta_u$, where β_{H_T} and β_{u_T} are the target uncertainty in the hazard curve and the target epistemic uncertainty of the fragility curves. These target uncertainties as well as the deviations from them can be established and specified by the governing code of reference. Differentiating equation (13), would lead to equation (14) which can be reasonably approximated by equation (15) for typical cases when β_H and β_u are of similar values and $K_H > 1$.

$$\Delta\beta_{PF} = (\beta_H\,\Delta\beta_H + K_H^2\,\beta_u\,\Delta\beta_u)/\beta_{PF} \tag{14}$$

$$\Delta\beta_{PF} = \frac{\Delta\beta_H}{K_H} + K_H\Delta\beta_u \tag{15}$$

Finally, combining equations (12) and (15), yields our proposed formulation for the design factor as described by equation (16), where the uncertainty term $\Delta\beta$ is described by equation (17).

$$DF^* = DF\,e^{-\Delta\beta\,X_q} \tag{16}$$

$$\Delta\beta = \frac{\Delta\beta_H}{K_H^2} + \Delta\beta_u \tag{17}$$

Equations (16) and (17) describe a design factor that is sensitive to the uncertainties involved in calculation of seismic hazards and fragility functions. Judicious selection of target uncertainties (β_{H_T} and β_{u_T}) corresponding to uncertainty values achieved using industry-wide best practices would allow appropriate and transparent incentives built in the determination of the DRS. Alternatively, the governing codes can specify best-practice methods with zero or even positive $\Delta\beta$ values and penalize more crude means and methods with enforcing a negative value for $\Delta\beta$. More research and involvement of the engineering community is necessary in establishing such guidelines.

Note that similar to mean-based risk-consistent DF, the formulation for DF^* also provides a risk consistent design response spectrum ($DRS^* = DF^* \times C_H$). The difference is that in this formulation, the DRS^* has a consistent q^{th} percentile of risk. Our recommendation is to use the 84th percentile of the annual probability of failure as the anchor point where $X_q = 1.0$.

COMPARISON WITH ASCE 43 FORMULATION

The performance-based formulation provided for calculation of the risk-consistent DRS by ASCE 43 in both 2005 and 2018 revisions is based on the mean-based risk-consistent formulation provided earlier. However, the ASCE 43 formulation is simplified for ease of use in a conservative manner as a function of a hazard slope parameter (AR, where $K_H = 1/\log(AR)$) and the dependency of the design factor (DF, ASCE 43-05) or scale factor ($SF = DF/AR$, ASCE 43-18) on the uncertainty of the mean fragility functions (β_c) is discarded. The ASCE 43-05 formulation is presented in equation (18). In these equations, $H_D = 10P_{TF}$, and C_{H_D} refers to the uniform hazard response spectrum at H_D hazard level.

$$DRS = DF \times C_{H_D}\ ;\ DF = max(1.0, 0.6AR^{0.8}) \tag{18}$$

The equivalent ASCE 43-18 formulation is presented in equation (19), where $H_P = P_{TF}$ and C_{H_P} refers to the uniform hazard response spectrum at H_P hazard level. Note that the minimum of 0.45 limit in equation (19) is added to avoid situations where for very low ground motions, the [log] linearity assumption for the hazard curve in the vicinity of P_{TF} does not hold.

$$DRS = SF \times C_{H_P} \; ; SF = max(AR^{-1}, 0.6AR^{-0.2}, 0.45) \tag{19}$$

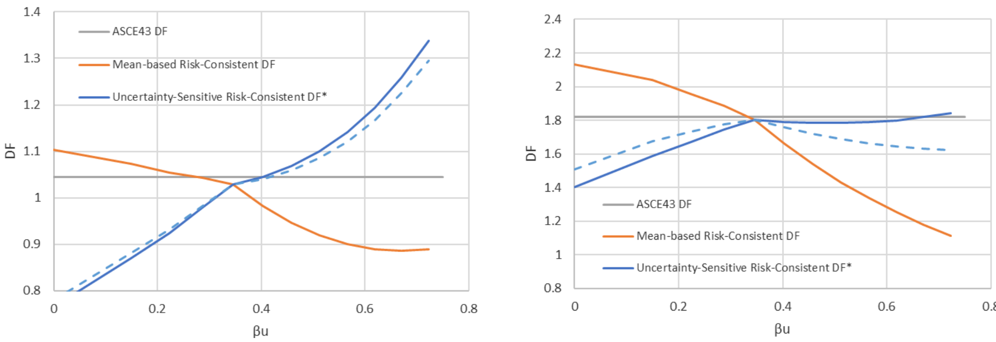
The variation of the mean-based (equation 7), uncertainty-sensitive (equation 16), and code (ASCE 43) design factors (equation 18) with respect to the variation of epistemic uncertainty of the fragility functions is demonstrated in Figure 1 (a) and (b) for $AR = 2$ and $AR = 4$ cases, respectively. The variation of the mean annual probability of failure (P_F) with respect to the variation of epistemic uncertainty of the fragility functions is also presented for the mean-based, uncertainty-sensitive, and code (ASCE 43) formulations using equation (4) in Figure 2 (a) and (b) for $AR = 2$ and $AR = 4$ cases, respectively. In the generation of these figures, the aleatory variability of the fragility curve is assumed to be $\beta_r = 0.2$, the target uncertainties are selected as $\beta_{H_T} = 0.45$ and $\beta_{u_T} = 0.35$, and target mean probability of failure is selected as $P_{TF} = 10^{-5}$, and $R_p = 10$. The uncertainty-sensitive formulation is shown for two cases: where the hazard curve uncertainty has a constant value of $\beta_H = 0.45$ (dashed line), and where it is assumed to vary from 0.25 to 0.80 (solid line) linearly correlated with the variation of the epistemic uncertainty. The following important observations are made:

1. As shown in Figure 1, the mean-based risk-consistent formulation results in a DF which has an undesirable inverse relationship with β_u. In other words, having larger epistemic uncertainty would result in a smaller design factor and thus smaller design response spectrum. This issue goes to the heart of the problem of having an irrational built-in disincentive for collecting information. This trend is clearly rectified in the uncertainty-sensitive risk-consistent formulation (the sensitivity of which can be adjusted by adjusting the X_q parameter discussed earlier). As expected, the ASCE 43 formulation is independent of the β_u.

2. For the mean-based formulation, the mean annual probability of failure remains equal to P_{TF} as observed from Figure 2. The simplified formulation of ASCE 43 for the DF is conservative for large values of β and results in a smaller mean probability of failure in these cases; thus, the ASCE 43 formulation is not in-fact a mean-based formulation. The degree of conservatism for the ASCE43 formulation, however, is not discussed nor rationalized in the code and cannot be reduced if better quality information is made available. The proposed uncertainty-sensitive risk-consistent formulation provides a similar degree of conservatism when β_u values are large, and it furthermore allows for relaxing the *mean* probability requirement when β_u values are small, following a clear dependence between the epistemic uncertainties involved and the degree of afforded conservatism. Thus, providing a rational incentive for collecting better quality of information.

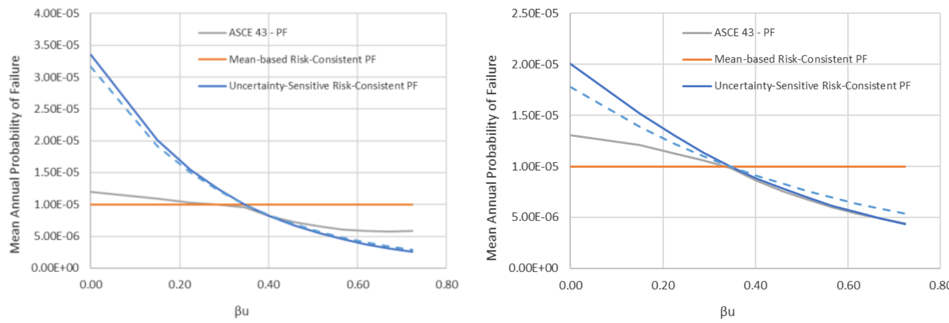
3. As shown in Figure 1 and Figure 2, the DF and PF calculated from the mean-based and uncertainty-sensitive formulations are equal at the target uncertainty values (in this case $\beta_u = 0.35$). In other words, if the data collection and analysis methodologies are consistent with practices used to establish target uncertainties, the same design factor and mean probability of failure is achieved using either formulation.

4. Comparing the solid and dashed blue lines in Figure 1 and Figure 2, the hazard curve uncertainties have a small impact on DF and PF values. This impact is consistent with the effect of β_u, i.e. larger values of β_H result in smaller DF and larger PF. More impact is observed for AR=4 case (smaller hazard curve slope, which is a characteristic of the CEUS motions).



(a) AR = 2.0 (b) AR = 4.0

Figure 1. Variation of design factor with respect to epistemic uncertainty of the fragility curve.



(a) AR = 2.0 (b) AR = 4.0

Figure 2. Variation of mean annual probability of failure with respect to epistemic uncertainty of the fragility curve.

CODE IMPLEMENTATION

The implementation of the proposed uncertainty-sensitive formulation in the design code would address the three challenges described earlier. In most cases, it is necessary to simplify the mathematical equations and complicated parameters before code adoption is possible. This is done to prevent misinterpretation of requirements and to allow code users who are not experts in a particular field to use the related provisions. Following this logic, we propose to use the existing ASCE 43 formulation for the design factor (DF, ASCE 43-05) or scale factor (SF, ASCE 43-18) multiplied by a factor, as shown in equation (20), for implementation in the code.

$$DF = DF_{ASCE43-05} \times e^{-\Delta\beta} \text{ or } SF = SF_{ASCE43-18} \times e^{-\Delta\beta} \tag{20}$$

The factor $e^{-\Delta\beta}$ can be interpreted as a *quality factor*. The term $\Delta\beta$ is obtained from equation (17) and is dependent on $\Delta\beta_H$ and K_H which should be readily available prior to the calculation of the design response spectrum (DRS) from the probabilistic seismic hazard analysis, and $\Delta\beta_u$ which can be cumulatively specified for different acceptable analysis methodologies elsewhere in future variations of the governing codes such as ASCE 1, ASCE 4, or ASCE 43. Of course, the code should also allow for explicit calculation of epistemic uncertainties using probabilistic methods.

For example, the use of both lumped-mass and stick models (LMSM) and finite element models (FEM) are acceptable practices as specified in ASCE 4. Accepting the FEM as the more desirable [target] approach, $\Delta\beta_u = 0$ can be specified for the use of typical FEM, $\Delta\beta_u = 0.1$ can be specified for a high quality FEM meeting certain prescribed criteria, and $\Delta\beta_u = -0.1$ may be assigned to the use of LMSM. Similarly, the uncertainty in the use of generic formulations for determination of seismic soil pressure can be acknowledged by using a $\Delta\beta_u = -0.15$ for such methods. The specification of $\Delta\beta_u$ factors should be done consistently throughout the governing codes of practice by experts knowledgeable and experienced in the implied uncertainties of the different methodologies prescribed by the code. The $\Delta\beta_u$ values would be additive for a certain response when multiple analysis methodologies contribute to its calculation. This would necessitate, defining different levels of the DRS prior to performing nonlinear analyses or applying the *quality factor* to the demands obtained from a linear analysis.

SIMPLIFIED EXAMPLE

The use of the proposed formulation is demonstrated using a simplified example of a soil layer over hard-rock site and a generic fragility function. Three cases are examined with moderate, low, and high epistemic uncertainties. The soil layer is defined by its thickness, shear-wave velocity, and damping ratio. The hard-rock is assumed as rigid. Equal aleatory uncertainty of 0.1 is assumed in all three cases.

The hard-rock hazard curves are defined with the mean hazard curve as well as 5th, 16th, 50th, 84th, and 95th fractiles. The target uncertainty of the hazard curves β_{H_T} is taken as 0.45 for this example. As discussed before, the difference between the fractile levels are used to estimate β_H. For this example, β_H for the low and high epistemic uncertainty cases are taken as $\frac{2}{3}$ or 1.5 times that of the moderate epistemic uncertainty case. A typical Central and Eastern United States (CEUS) hazard curve is used for this example.

The fragility uncertainty effects are included by defining $\Delta\beta_u$ values of 0, 0.1, and -0.1 (e.g. having FEM, high quality FEM, and LMSMs for the structure(s) involved) for the moderate, low, and high epistemic uncertainty cases, respectively. The soil parameters used are summarized in Table 1.

Table 1. The parameters used in the epistemic uncertainty cases defined for the simplified example

		Epistemic uncertainty defined in terms of logarithmic standard deviation		
	Median Values	**Moderate**	**Low**	**High**
Shear-wave velocity	1500 ft/s	0.15	0.1	0.3
Soil layer thickness	25 ft	0.1	0.05	0.2
Shear-wave damping ratio	0.05%	0.15	0.1	0.3

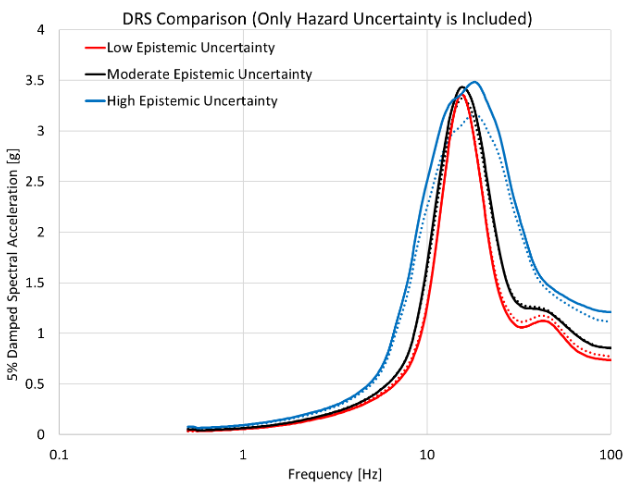
The transfer function of the site response for soil over rigid rock is readily available in closed form Kramer (1996). To propagate the uncertainties involved, we examined the site response using combinations of the 10th, 50th, and 90th percentiles with weights of 0.3, 0.4, and 0.3, respectively, for each of the three parameters involved, i.e. a total of 27 branches. For simplicity, we did not assume any nonlinearity in the soil properties. The soil amplification functions corresponding to the transfer functions are calculated using random vibration theory (RVT, Lutes and Sarkani (2004)) and the surface hazard curves are calculated by integrating the amplification functions and the rock hazard curves following the so-called Approach 3 method of NUREG/CR 6728 (McGuire, et al. (2001)).

For the calculated surface hazard, the UHRS at 10^{-4} and 10^{-5} are calculated for each case as well as their corresponding β_H for which the values for 10^{-5} are used going forward. Finally, taking $P_{TF} = 10^{-5}$, the DRS is calculated using the ASCE 43 formulation in equations (18) and (19) and presented in Figure 3. The uncertainty-sensitive DRS is calculated using equation (20) for the moderate, low, and high epistemic uncertainty cases and presented in Figure 3. We make the following observations:

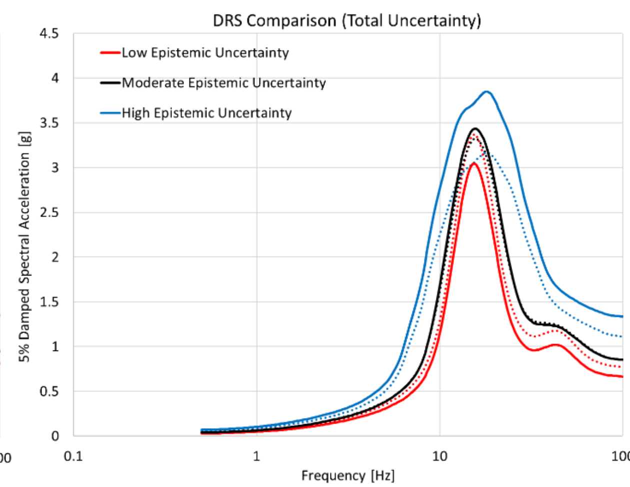
1. The potential irrational outcome of the current mean-based ASCE 43 formulation is observed in Figure 3 (a) where at the peak frequency of approximately 15 Hz, the case with highest epistemic uncertainty would provide the lowest design response spectrum. Conversely, as seen in Figure 3 (b), the uncertainty-sensitive risk-consistent formulation ensures a more rational design input where the input motion is largest when we are more uncertain about the input parameters. Note that with both ASCE 43 and uncertainty-sensitive formulation, the DRS corresponding to the case with more uncertainty is broader than the case with less uncertainty. This reflects the uncertainty in the resonance frequency of the site and is indeed appropriate. Because target uncertainty is achieved in

the moderate uncertainty case, the uncertainty-sensitive risk-consistent formulation provides essentially the same DRS when compared to the ASCE 43 formulation.

2. Comparison between Figure 3 (a) and (b) demonstrate the relative effects of uncertainties on the hazard and fragility sides. As shown in equation (17), the effect of the hazard uncertainties $\Delta\beta_H$ is reduced by dividing it by the square of the frequency dependent slope factor K_H (which in this example ranges from 1.7 to 2.3), while the fragility epistemic uncertainties ($\Delta\beta_u$) effects the response as a frequency independent scale factor. Therefore, for the same change in hazard and fragility uncertainties, the effect of the latter on the DRS is more significant.
3. The use of the uncertainty-sensitive risk-consistent formulation offers a clear incentive to reduce uncertainties. In this example, Figure 3 (b) provides a clear tool of communication between the designers and owners to show the value gained by the use of more accurate modelling techniques, improvements in site investigations, and obtaining better quality information.
4. For the uncertainty-sensitive risk-consistent formulation, the PF (mean annual probability of failure) is calculated in the low, moderate and high uncertainty cases using equation (10) as 1.3×10^{-5}, 1.0×10^{-5}, and 0.73×10^{-5}, respectively (average value over all frequencies is reported here). As intended, the proposed formulation provides a more conservative PF, in comparison with the target performance $P_{TF} = 1 \times 10^{-5}$, when more uncertainty is present.
5. For the uncertainty-sensitive risk-consistent formulation, the β_{PF} (uncertainty of the annual probability failure) is calculated for the low, moderate and high uncertainty cases using equation (13) as 0.58, 0.83, and 1.1, respectively (average value over all frequencies is reported here). As discussed before, these uncertainties are inherently large. The results of this example suggest an expected uncertainty of about 0.8 as the target for PF and a typical range of 0.6 to 1.1.



(a) Hazard Uncertainty Only



(b) Total Uncertainty

Figure 3. Comparison of the DRS obtained using ASCE 43 formulation (dotted lines) and the proposed formulation (solid lines) for the simplified example with different levels of epistemic uncertainties.

EXAMPLES FROM CURRENT AND RECENT PROJECTS

In order to demonstrate the application of the proposed uncertainty-sensitive formulation on the DRS calculated for recent projects, a few examples are presented. These DRS represent the SSE for their respective buildings.

The first example is the DRS calculated for Service Building (SB), Auxiliary Building (AB), and Service Water Pump House (SWPH) for a nuclear power plant in CEUS. The hazard evaluation for this plant is carried out using rigorous evaluation of uncertainties in the underlying PSHA and site response evaluation, the estimated hazard uncertainty for PGA at 1e-5 mean annual frequency of exceedance is

$\beta_H = 0.39$. Using the target hazard uncertainty of $\beta_{H_T} = 0.45$, leads to $\Delta\beta_H = \beta_{H_T} - \beta_H = 0.06$. The analysis methodology included for the SB incorporates a simplified FEM model which meets the essential requirements of dynamic modelling but utilizes important practical simplifications. For this building the $\Delta\beta_u = 0$ is judged adequate. For the AB, the analysis model incorporates a rather detailed FEM incorporating as-built information for most relevant structural parameters. As such the $\Delta\beta_u = 0.1$ is considered for this building. Conversely, the SWPH is evaluated using a LMSM and important simplifying [conservative] assumptions, suggesting the choice of $\Delta\beta_u = -0.1$. For these cases, the DRS obtained using the current ASCE 43 formulation and modified per the proposed uncertainty-sensitive formulation. The impact of the reduced uncertainty in the hazard calculation is most clearly observed in the results for SB (where $\Delta\beta_u = 0$), in this case an average (over all frequencies) reduction of 1.5% is obtained using the proposed formulation. The additional effects of accuracy of the modelling methodology can be observed in the results for AB and SWPH. The DRS calculated for the AB and SWPH are on average reduced by 11% and increased by 9.5%, respectively, reflecting the combined effects of low hazard uncertainty and level of uncertainty implied by the choice of downstream analysis methods for each building.

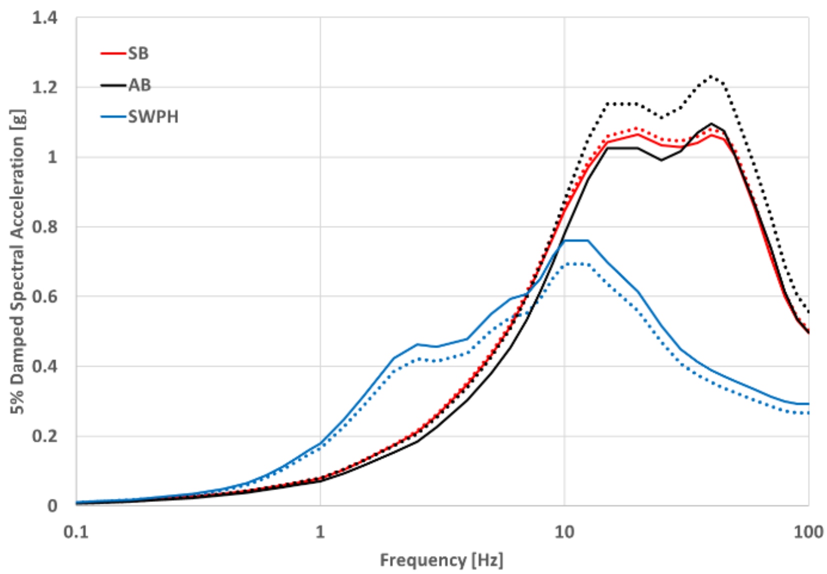


Figure 4. Comparison of the DRS obtained using ASCE 43 formulation (dotted lines) and the DRS obtained using the proposed formulation (solid lines) for different nuclear buildings.

The second example we present is the DRS calculated for another nuclear power plant as the site ground motion response spectra (GMRS). Because of limited data for this site, larger epistemic uncertainties were considered for the site amplification calculation underlying its GMRS calculation. The resulting estimate hazard uncertainty for PGA at 1e-5 mean annual frequency of exceedance is $\beta_H = 0.49$. The GMRS serves as the SSE for the site and can be used as DRS in analysis of different SSCs with different levels of analytical rigor. For demonstration, the DRS calculated using ASCE 43 and proposed uncertainty-sensitive formulation are compared for analytical methods consistent with $\Delta\beta_u$ values of zero, -0.1 (large epistemic uncertainty), and 0.1 (small epistemic uncertainty) in Figure 5. The impact of the increased uncertainty in the hazard calculation is observed in the results for the case with $\Delta\beta_u = 0$, where a small average increase of 0.5% is obtained using the proposed formulation. The additional effects of accuracy of the modelling methodology can be observed in the results for cases with $\Delta\beta_u = 0.1$, and $\Delta\beta_u = -0.1$. The DRS calculated for the former (low epistemic uncertainty) is on average reduced by 9% and for the latter (high epistemic uncertainty) is increased by 11.1%, reflecting the combined effects of hazard uncertainty and level of uncertainty implied by the choice of downstream analysis methods for each building.

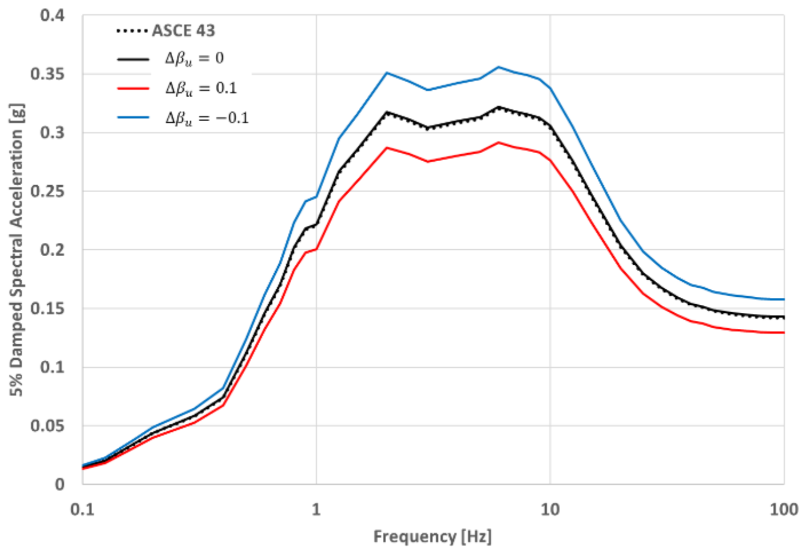


Figure 5. Comparison of the DRS obtained using ASCE 43 formulation (dotted line) and DRS obtained using the proposed formulation (solid lines) for a site with large hazard uncertainty.

CONCLUSIONS

We point out that the current approach as stated in ASCE 43-05 and ASCE 43-18 for determination of the safe shutdown earthquake (SSE) for nuclear facilities does not include an explicit incentive for reducing epistemic uncertainties involved. We argue that reduction of epistemic uncertainties should be a goal of the governing design and analysis codes and provide rigorous and simplified formulations for such explicit inclusion. Finally, using both hypothetical and actual examples, we demonstrate that the proposed formulation is equivalent to the current approach for a site with "reasonable" epistemic uncertainty and that for the same performance criterion, the SSE would increase with increasing epistemic uncertainty and decrease with a reduction in the epistemic uncertainty. In other words, "knowledge" is rewarded and lack-thereof is penalized.

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