Natural Phenomena Hazards October 2020 Meeting

RISK-CONSISTENT VERTICAL GROUND MOTION SPECTRA

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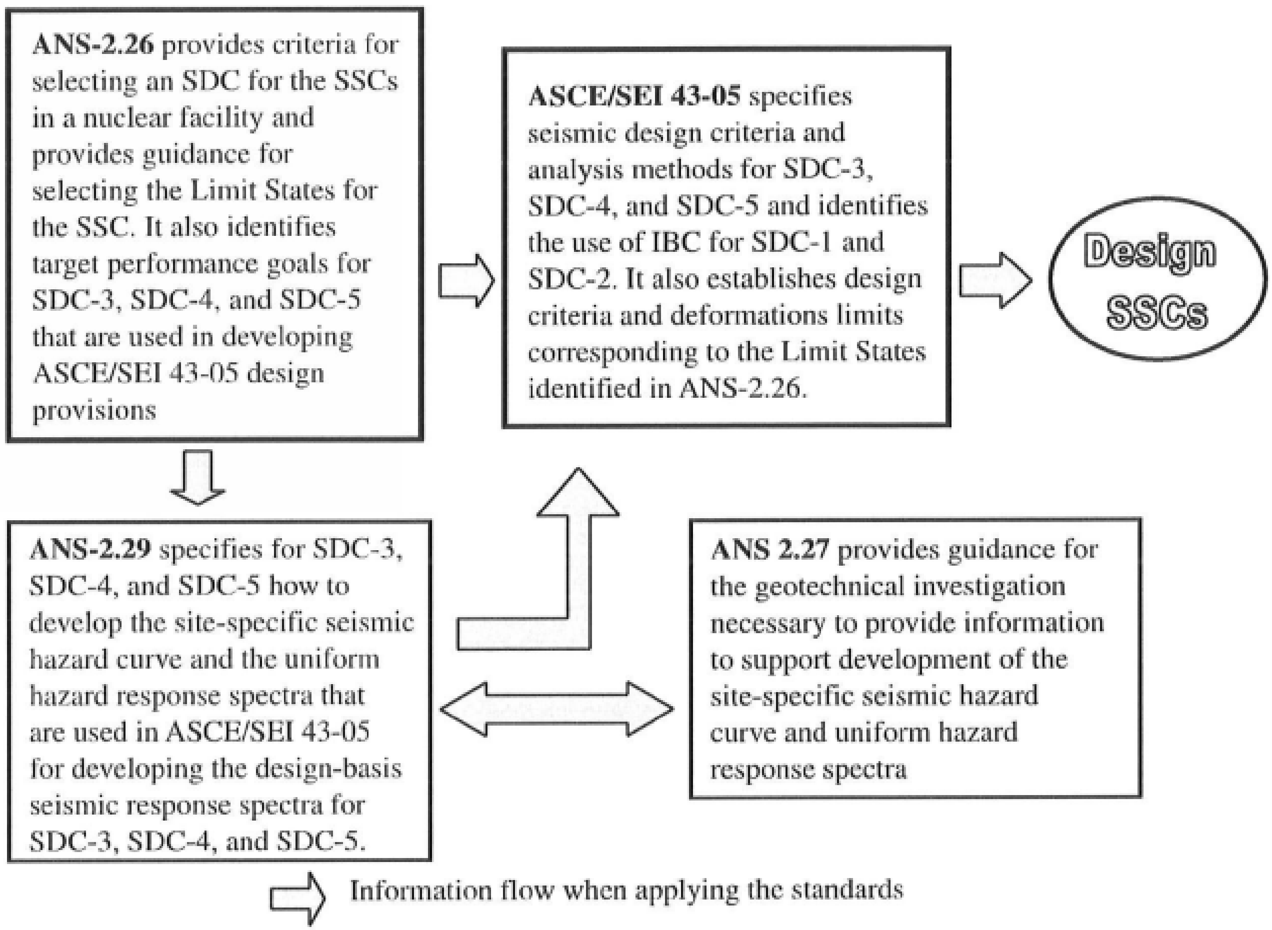
Outline

- Background on performance-based design response spectrum (DRS)
- Current Practice for Vertical DRS
- Motivation for Risk-Consistent Vertical DRS
- Proposals for Risk-Consistent Vertical DRS
- Development of Risk-Consistent Adjustment Factor
- Conclusions

Input Motion for Performance-Based Design

- Seismic performance for SSCs with serious failure consequences is recognized by the designation of a seismic design basis (SDB), which varies by SSC
- The SDB for nuclear facilities is defined by
  - (1) acceptable level of damage or limit state (LS), and
  - (2) a seismic design category (SDC) 1 through 5
- SDC determines the annual frequency of exceedance (AFE) of acceptable performance level (*Target performance goal (P_F) – defined in ANS 2.26*)
- More serious consequences of unacceptable performance → Higher SDCs Higher SDC requires lower P_F to achieve approximately balanced risk through different SDCs
- Lower P_F is achieved by higher design basis earthquake (DBE)

Nuclear Seismic Design Standards



(Figure extracted from ANS-2.26)

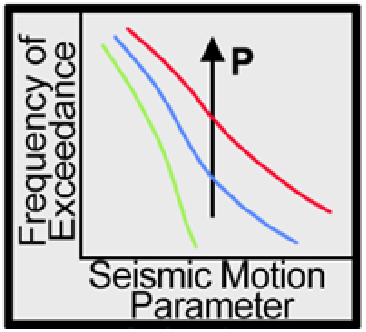
Performance Objective

Performance computed by risk convolution integral

- Probabilistic seismic hazard curve for A_{REF}
- Seismic fragility function

A_{REF}: Reference ground motion spectrum parameter, e.g., horizontal PGA

The risk convolution integral is strongly influenced by the slope of the hazard curve



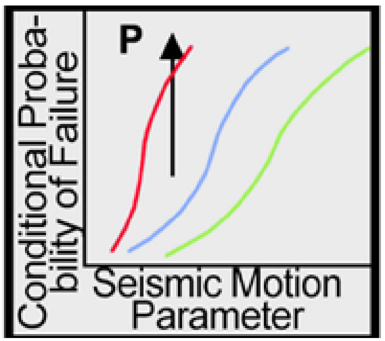
Seismic Hazard Curve

“Linear” in log-log space. Defines the UHRS shape, which is used in fragility.

Hazard curve slope

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

Fragility function



Fragility Curve

(Adapted from EPRI 3002012994)

$A = A_m \, \varepsilon_R \, \varepsilon_U$

$A_m = F_{Sm} \, A_{REF}$

$\beta = SQRT[\beta_R^2 + \beta_U^2]$

Input Ground Motion Spectrum

***Selection of the seismic ground motion (DRS* for Design, *RE* for SPRA)** is critical

The goal is:

- Identify the design response spectra (DRS) representing DBE that achieves the performance goal

To achieve the performance goal, ASCE 43 defines the DRS as:

$$DRS = SF \times UHRS_{Hp}$$

where $UHRS_{Hp}$ is the UHRS determined for exceedance frequency H_p and SF is the scale factor, which is function of slope factor (A_R), a function of $\frac{-dH(a)}{da}$

Vertical DRS Ground Motion

Common Methods in Practice:

  - Apply vertical-to-horizontal (V/H) ratios to the horizontal DRS
  - Apply the SF factors calculated for the horizontal DRS to the vertical UHRS

- Both approaches result in ***hazard- consistent*** vertical motion, and ***not risk-consistent***

- Vertical ground motion hazard can have very different ***slope***

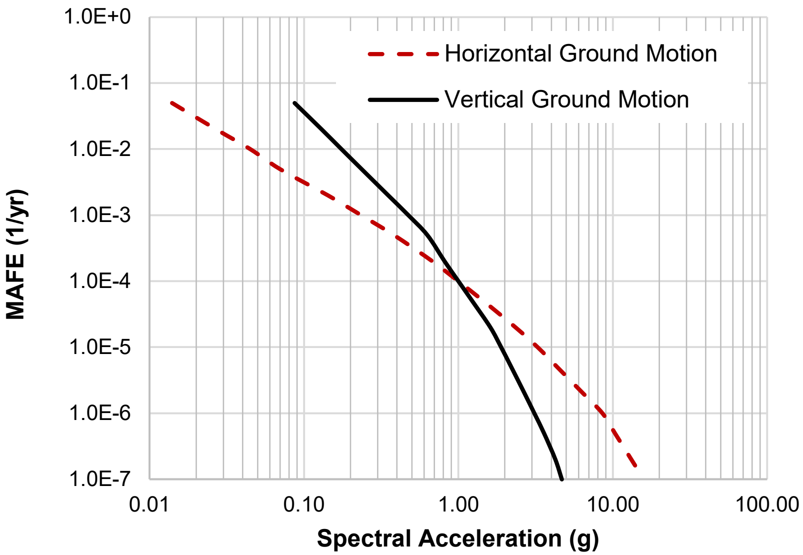
- It is a common simplification since vertical ground motion is usually a secondary contributor to limit-states for most components

- If vertical motion governs limit-state of a component, e.g., shear in a beam, the vertical DRS **may not result in** meeting the ***target performance goal***

Horizontal vs Vertical Hazard Curves

- Slope of horizontal and vertical hazard curves are dissimilar

- Hazard-consistent vertical DRS introduces performance bias for components **governed** or strongly **influenced** by **vertical motion (conservative or unconservative)**
- Bias can be up to ~50% in mean risk for these components
- Magnitude of bias depends on difference in hazard curve slopes



Example horizontal and vertical hazard curves

Methods for Risk-Consistent Vertical Spectrum

Starting from a Clean Slate

- Apply V/H ratios to the the horizontal UHRS at MAFEs = H_p and $10H_p$
- Develop independent SF factors for the resulting vertical UHRS
- Results in risk-consistent vertical DRS that account for difference in slope

Starting from an Existing Design / Analysis

- Many analyses already have DRS defined, ground motion suites developed and response analyses performed
- Redoing the ground motion selection and analyses is certainly not desired and may not be feasible
- Existing analyses can be backfitted to follow a risk-consistent vertical DRS by applying a calibrated adjustment factor to the original vertical spectrum
  - This corresponds to multiplying the vertical input motions by a constant
  - For equivalent linear analyses → multiply vertical response results by constant

Risk-Consistent Adjustment Factor

Hazard-consistent vertical DRS × $\boxed{\text{Adjustment Factor}}$ = Risk-consistent vertical DRS

Criterion

- Find a scalar adjustment factor such that:

*P_F calculated using **risk-adjusted** vertical DRS convolved w. **horizontal** hazard curve*
=
*P_F calculated using **hazard-consistent** vertical DRS convolved w. **vertical** hazard curve*

Multiple the adjustment factor by the hazard-consistent vertical DRS to **approximate** a risk-consistent vertical DRS

Approximate only since an average frequency-independent value is used

Risk-Consistent Adjustment Factor (cont.)

The risk-consistent adjustment factor is given by λ:

$$\lambda = \{(F_{Sm})^{K_{Hv}-K_{Hh}} \exp[0.5\,\beta^2\,(K_{Hh} - K_{Hv})]\}^{1/K_{Hh}}$$

- Scale factor: F_{Sm}
- Variability / dispersion in the fragility function : β
- Slopes of the horiz. and vert. hazard curves betw. H_P and $10H_p$: K_{Hh} & K_{Hv}

F_{Sm}, is expected margin to the **median** seismic capacity of the facility

λ is not strongly sensitive to β (next slide)

K_{Hh} & K_{Hv} are the primary factors in determining the adjustment factor

λ is generally frequency-dependent as K_{Hh} & K_{Hv} are (similar to V/H ratio)

Example Risk Estimate of Bias

Potential out of plane or punching shear failure of slab

- The performance (P_F /yr) is quantified by convolving the seismic fragility and hazard in terms of the vertical ground motion directly, β = 0.40 → 8.6E-6/yr
- Exact solution uses vertical hazard curve in the risk convolution integral
- Hazard-consistent DRS case convolves horizontal hazard curve and fragility from hazard-consistent slab vertical demand → results in bias in P_F
- Risk-consistent DRS case convolves horizontal hazard curve and fragility from risk-adjusted slab vertical demand (λ = 0.93) → P_F matches the exact solution

$(A_{R,v} / A_{R,h}) = 0.6$

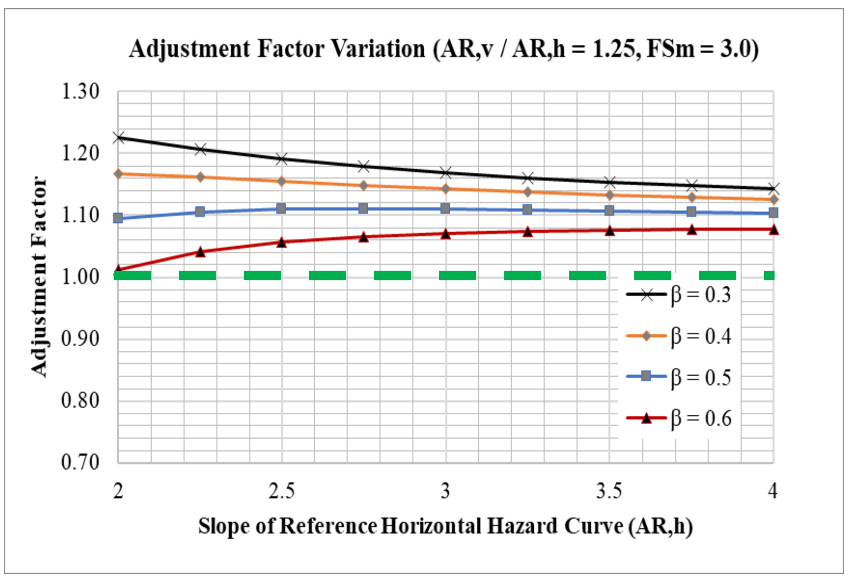
Vertical DRS	Calculated Risk (/yr)	Ratio to Exact Risk Estimate
Exact Solution	8.60E-06	1
Hazard-consistent DRS	1.10E-05	1.27
Risk-consistent DRS	8.60E-06	1

~30% bias

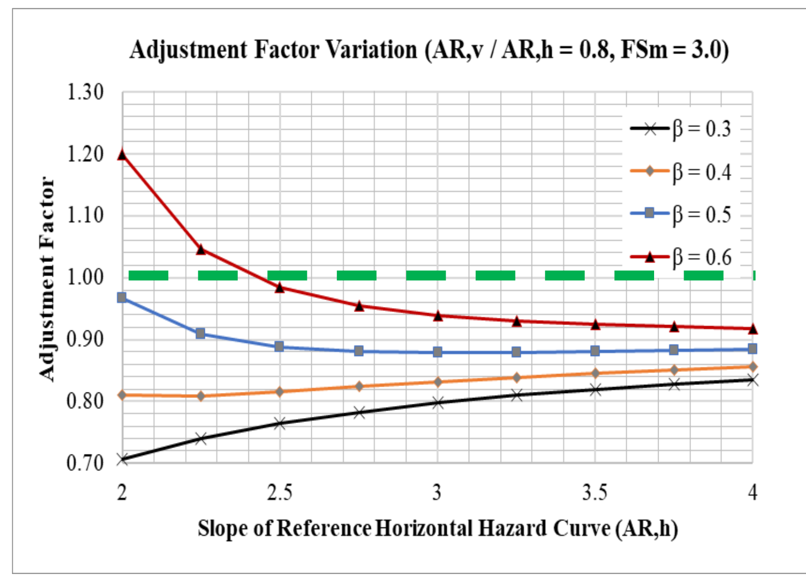
Properties of λ

Plots show influence of horiz. hazard curve slope $A_{R,h}$, for a typical F_{Sm} = 3.0

- Typical hazard curve slopes are between 2 and 4
- When the vertical hazard curve slope is 25% flatter than the horizontal (left) , λ is practically between 1.0 and 1.2
- When the vertical hazard curve slope is 25% steeper than the horizontal (right), λ is largely between 0.75 and 1.0
- For practical cases, sensitivity to β is less than ± 0.1



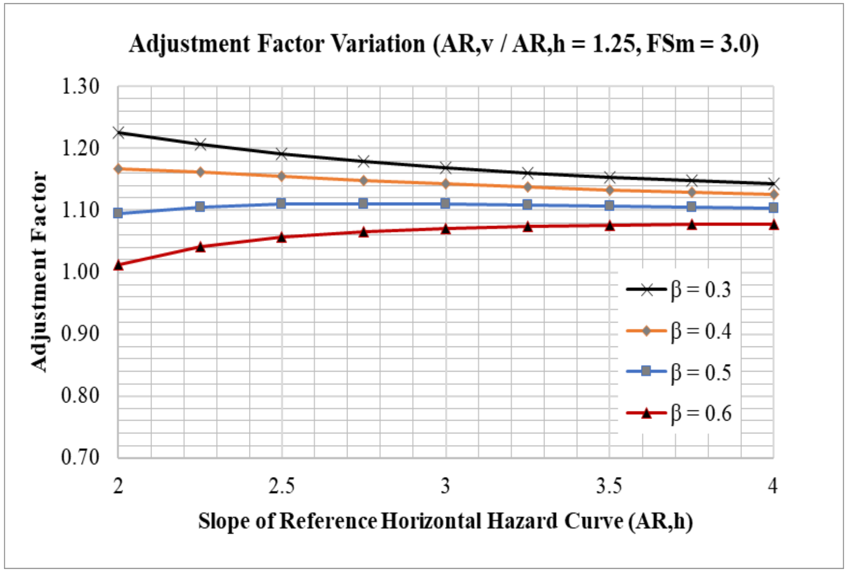
Ignoring λ is unconservative



Ignoring λ is conservative

Sensitivity of λ to β

- Dependence on β is typically mild with other parameters constant, < ±0.1
  - A λ can be selected representative of values within the range of β
  - Additional variability can be included in vertical ground motion to capture uncertainty in λ values within range of β
  - Sensitivity study indicated that this variability is minor vs. variability in V/H ratios, and can be ignored



Conclusions

- Common approaches for developing vertical DRS may result in deviation from intended performance goal for some components
- The reason is the difference in slope of the horizontal and vert hazard curves, a key parameter in the risk convolution integral
- Risk-consistent vertical DRS can be developed by
  - Developing scale factors for the vertical DRS independent of the horizontal DRS
  - Adjusting hazard-consistent vertical DRS
- Adjustment has practical advantages for existing analyses
- Adjustment factor, λ
  - Strongly influenced by slopes of hazard curves
  - Only mildly influenced by β for typical range of β
  - Generally frequency-dependent but can be approximated as constant
- The developed adjustment factor method is practical and applicable to both performance-based design and SPRA applications

Thank you