Risk-informed, performance-based seismic design of nuclear structures

Brian McDonald, Ph.D., S.E.
Vice President, Exponent
Andrew Whittaker, Ph.D., S.E.
SUNY Distinguished Professor, University at Buffalo
Sai Sharath Parsi, Ph.D.
X-energy

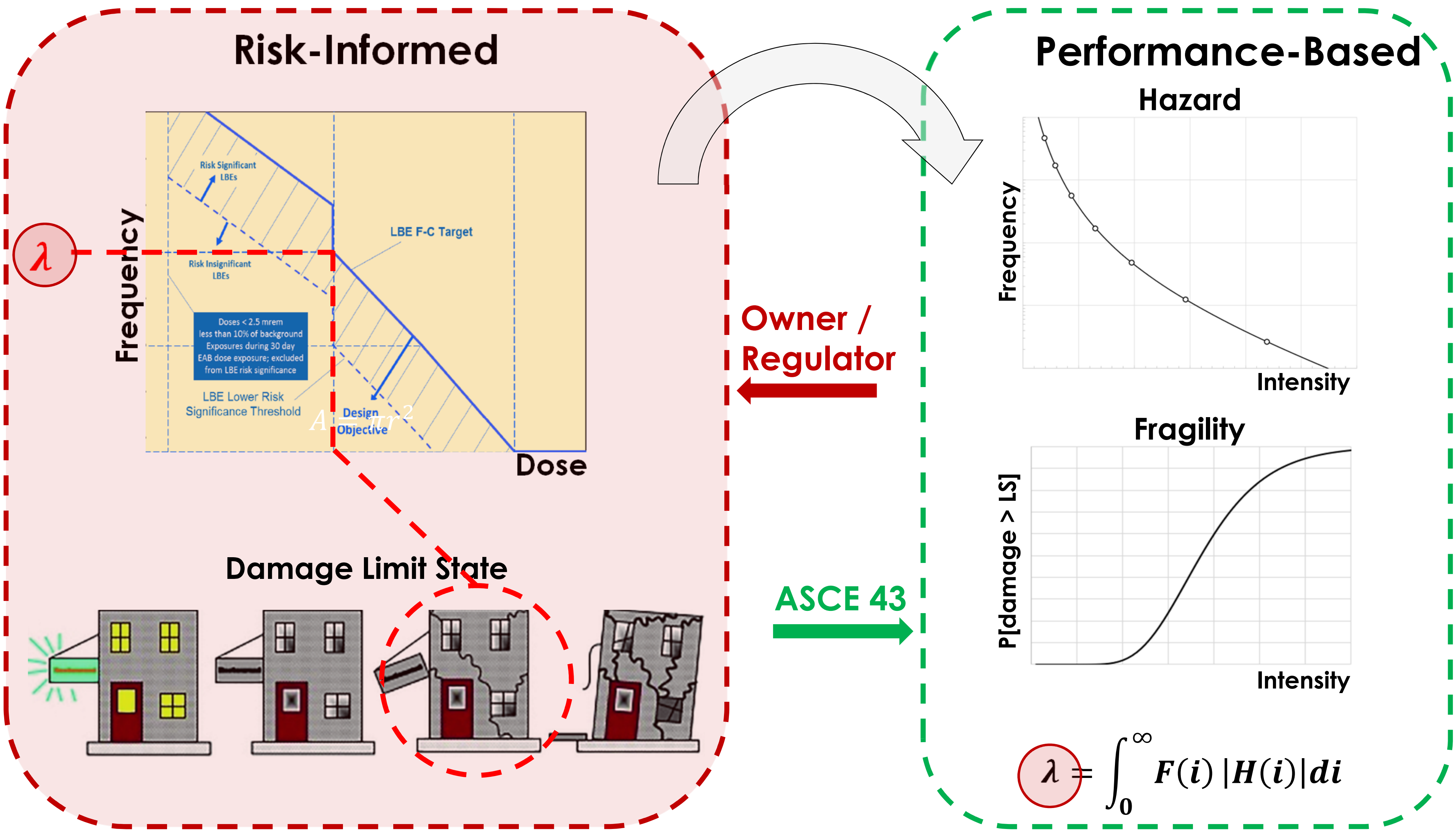
USNRC Standards Forum, September 25, 2025

Three points to take away

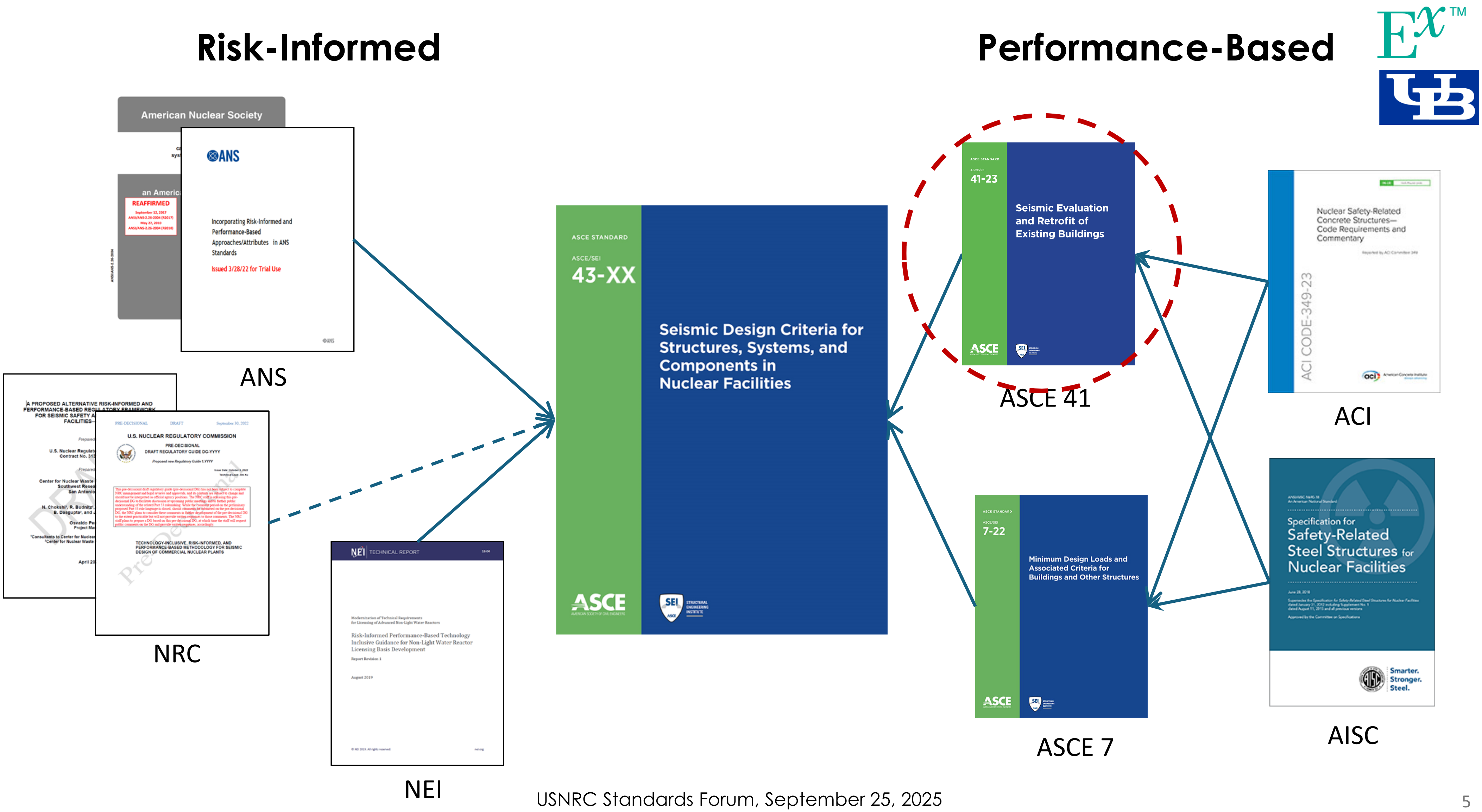
- ASCE standard has been RIPB since 1990s, so no fundamental rewrite
- Civil structures are different animals with their own needs (e.g., QA/QC)
- RIPB nuclear standards need to catch up to RIPB commercial standards

Three points to take away – for reference

- **RIPB** seismic design has already underpinned ASCE standards for seismic design of nuclear structures for three decades
  - **RI** by other SDOs (e.g., allowed exceedance rate for damage limit state)
  - **PB** by ASCE standards (e.g., design spectral acceleration to achieve **RI**)
- Design and on-site construction of reinforced concrete and structural steel differ fundamentally from design, fabrication and installation of mechanical / electrical plant systems, and our standards should reflect that
  - Each site is unique (soils, topography, seismicity) leading to unique designs
  - Built essentially on-site, often with local labor and materials
  - Failures are almost always due to conspicuously poor design or construction, not from small, hidden defects or progressive damage
- **RIPB** is not unique to nuclear structures. In commercial space, the accumulated RIPB design and construction experience includes thousands of safety critical structures (e.g., California high-rises, hospitals, clinics, schools), and it is incumbent on us to include lessons learned into our nuclear standards:
  - Mature, proven QA/QC procedures developed for safety critical civil structures
  - Laboratory-tested and field-proven structural designs and detailing
  - Demonstrated benefits of design peer review and on-site structural engineer inspector
  - Use of latest USGS seismic hazard tools (with expert insight) rather than PSHA / SSHAC



Risk-Informed
Frequency
Dose
Risk Significant LBEs
Risk Insignificant LBEs
LBE F-C Target
Doses < 2.5 mrem less than 10% of background Exposures during 30 day EAB dose exposure; excluded from LBE risk significance
LBE Lower Risk Significance Threshold
Design Objective
λ
Damage Limit State
Owner / Regulator
ASCE 43
Performance-Based
Hazard
Frequency
Intensity
Fragility
P[damage > LS]
Intensity
$\lambda = \int_0^\infty F(i)\,|H(i)|\,di$

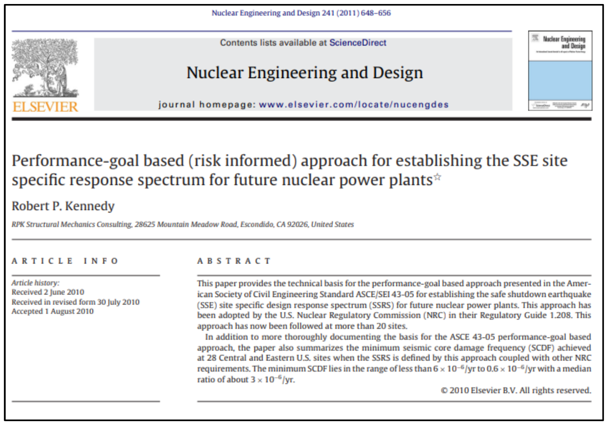

Risk-Informed
Performance-Based
ANS
NRC
NEI
ASCE STANDARD
ASCE/SEI
43-XX
Seismic Design Criteria for Structures, Systems, and Components in Nuclear Facilities
ASCE 41
Seismic Evaluation and Retrofit of Existing Buildings
41-23
ASCE 7
7-22
Minimum Design Loads and Associated Criteria for Buildings and Other Structures
ACI
ACI CODE-349-23
Nuclear Safety-Related Concrete Structures—Code Requirements and Commentary
AISC
Specification for Safety-Related Steel Structures for Nuclear Facilities
Smarter. Stronger. Steel.
Incorporating Risk-Informed and Performance-Based Approaches/Attributes in ANS Standards
Issued 3/28/22 for Trial Use
U.S. NUCLEAR REGULATORY COMMISSION
Risk-Informed Performance-Based Technology Inclusive Guidance for Non-Light Water Reactor Licensing Basis Development

Primary goals for the revision of ASCE 43

- General cleanup – eliminate stuff covered by other SDOs
- Update technical bases
  - Update performance-based provisions for design basis acceleration (Parsi)
  - Update design parameters to state-of-the-practice (ASCE 41)
  - Update acceptance criteria to include NLRHA (routine elsewhere)
- Update Quality Assurance requirements to reflect civil structures, while meeting intent of 10 CFR Part 50 Appendix B
- Update seismic hazard provisions to allow USGS tools

Kennedy framework

Closed-form solution to risk integral


Nuclear Engineering and Design 241 (2011) 648–656

Contents lists available at ScienceDirect

Nuclear Engineering and Design

journal homepage: www.elsevier.com/locate/nucengdes

Performance-goal based (risk informed) approach for establishing the SSE site specific response spectrum for future nuclear power plants☆

Robert P. Kennedy

RPK Structural Mechanics Consulting, 28625 Mountain Meadow Road, Escondido, CA 92026, United States

ARTICLE INFO

Article history:
Received 2 June 2010
Received in revised form 30 July 2010
Accepted 1 August 2010

ABSTRACT

This paper provides the technical basis for the performance-goal based approach presented in the American Society of Civil Engineering Standard ASCE/SEI 43-05 for establishing the safe shutdown earthquake (SSE) site specific design response spectrum (SSRS) for future nuclear power plants. This approach has been adopted by the U.S. Nuclear Regulatory Commission (NRC) in their Regulatory Guide 1.208. This approach has now been followed at more than 20 sites.

In addition to more thoroughly documenting the basis for the ASCE 43-05 performance-goal based approach, the paper also summarizes the minimum seismic core damage frequency (SCDF) achieved at 28 Central and Eastern U.S. sites when the SSRS is defined by this approach coupled with other NRC requirements. The minimum SCDF lies in the range of less than 6×10^{-6}/yr to 0.6×10^{-6}/yr with a median ratio of about 3×10^{-6}/yr.

© 2010 Elsevier B.V. All rights reserved.

(Kennedy, 2011)

C1.5 ALTERNATIVE METHODS TO MEET THE INTENT OF THIS STANDARD

The DBE ground motion is defined in Equation (2-1) in terms of a design response spectrum (DRS). Structures whose elements are designed for DRS demands using design capacities derived in accordance with referenced materials standards, as modified in this standard, are expected to achieve the target performance goal listed in Table 1-1. The DRS is formulated to achieve both of the following:

1. Less than about a 1% probability of unacceptable performance for the DBE ground motion, and
2. Less than about a 10% probability of unacceptable performance for a ground motion equal to 150% of the DBE ground motion.

(ASCE 43-19)

Linearized (log-log) hazard curve

$$Hazard(a) = K_1 \times a^{-K_H}$$

$$K_H = \frac{1}{\log(A_R)},\ K_1 = \frac{\lambda}{a_\lambda^{-K_H}},\ \text{and } A_R = \frac{a_\lambda}{a_{10\lambda}}$$

Lognormal fragility function

$$Fragility(a,\mu,\beta)$$

Rigorous seismic risk equation

$$\lambda = \int_0^\infty -\left(\frac{dHazard(a)}{da} \times Fragility(a,\mu,\beta)\right) da$$

Simplified, closed-form risk equation

$$\lambda = K_1 \times (e^\mu)^{-K_H} \times e^{\frac{1}{2}(\beta\times K_H)^2}$$

$$C_p = a_\lambda e^{\left(\frac{1}{2}\beta^2 K_H + \beta\Phi_p^{-1}\right)}$$

Design and assessment shaking

$$C_{1\%ile} = a_\lambda e^{\left(\frac{1}{2}\frac{\beta^2}{\log(A_R)} - 2.326\beta\right)}$$

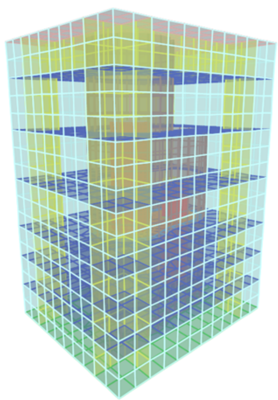
$$C_{10\%ile} = C_{1\%ile} \times e^{1.05\beta}$$

Kennedy showed how the target fragility function could be determined from the uniform hazard response spectrum (UHRS), the slope of the hazard curve near the performance goal (A_R), and the dispersion (β).

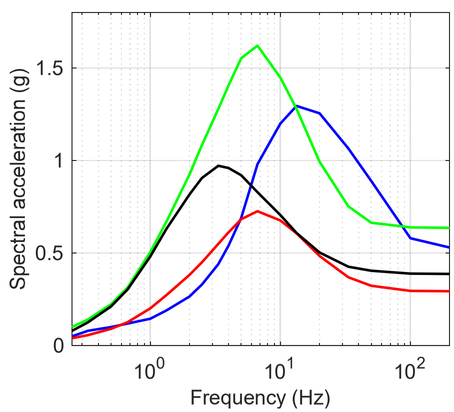
A comprehensive study to ensure the design provisions properly incorporated A_R and β given updated hazards and nonlinear simulations.

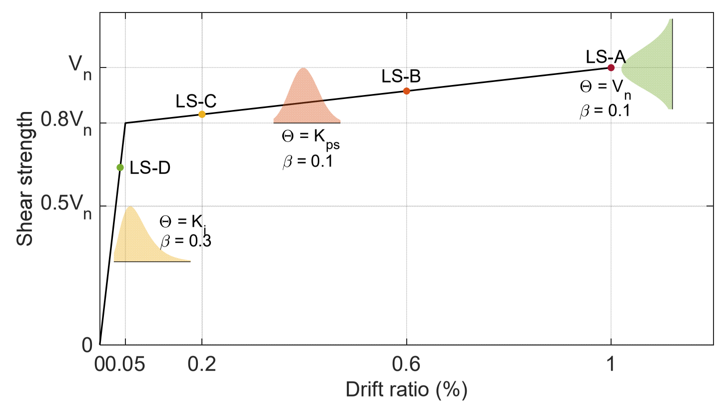
New (but really just tweaked) design equations will be balloted based on these results to satisfy dual intent (1% at DRS, 10% at 150% DRS).

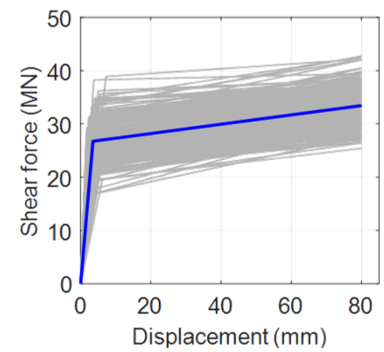
Dispersion analysis: results from Monte-Carlo simulations

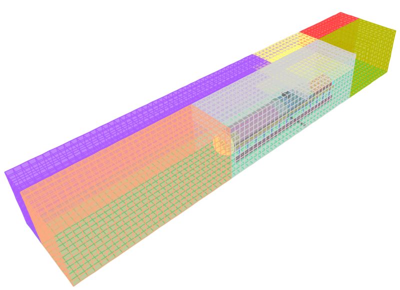


(Parsi *et al.*, 2022)

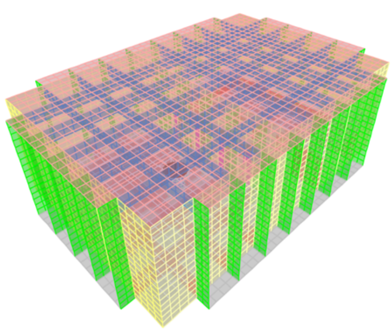




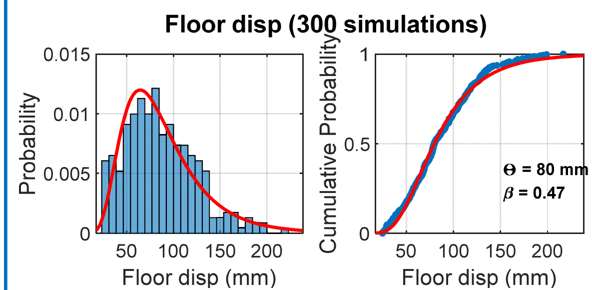




(Parsi *et al.*, 2024)



(Parsi *et al.*, 2022)



Composite $\beta = \sqrt{\beta_{MC}^2 + \beta_{mf}^2 + \beta_c^2} = 0.5$

0.47 0.1 0.15

β for LS-A = 0.5

β for LS-A = 0.5

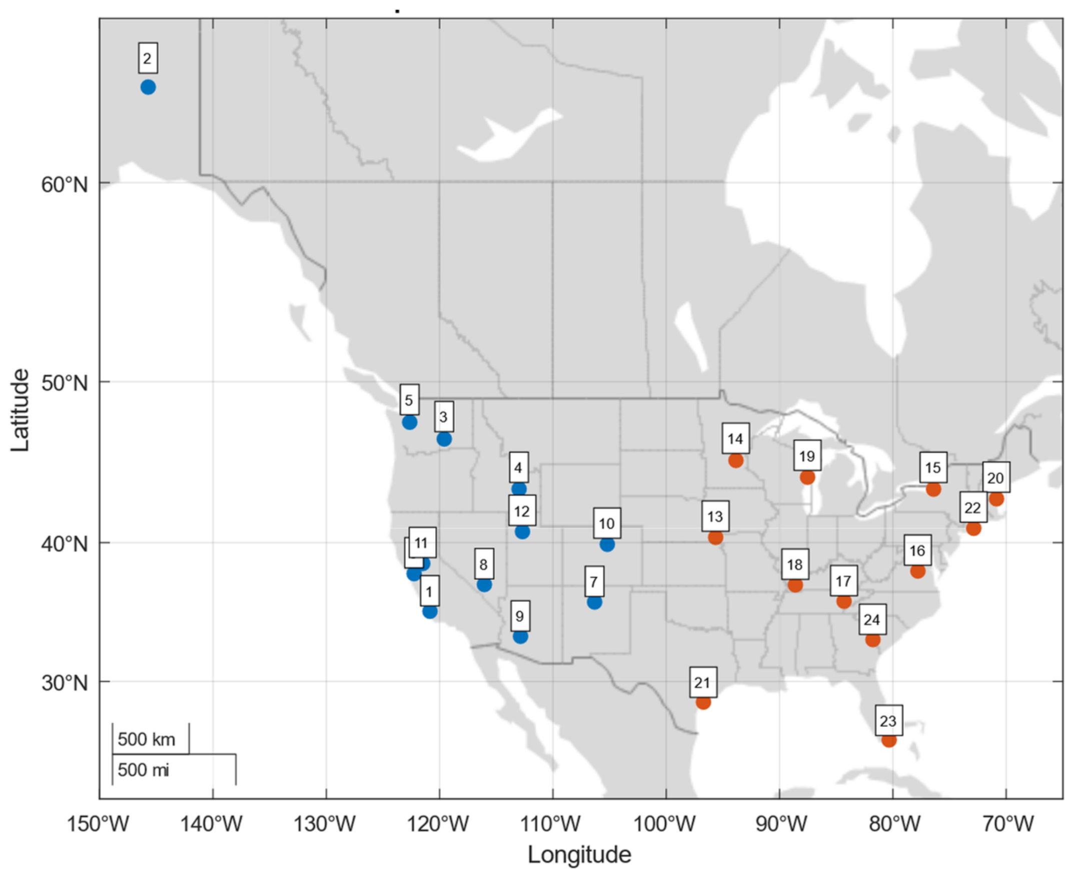
β for LS-B = ..

β for LS-C = ..

0.4?

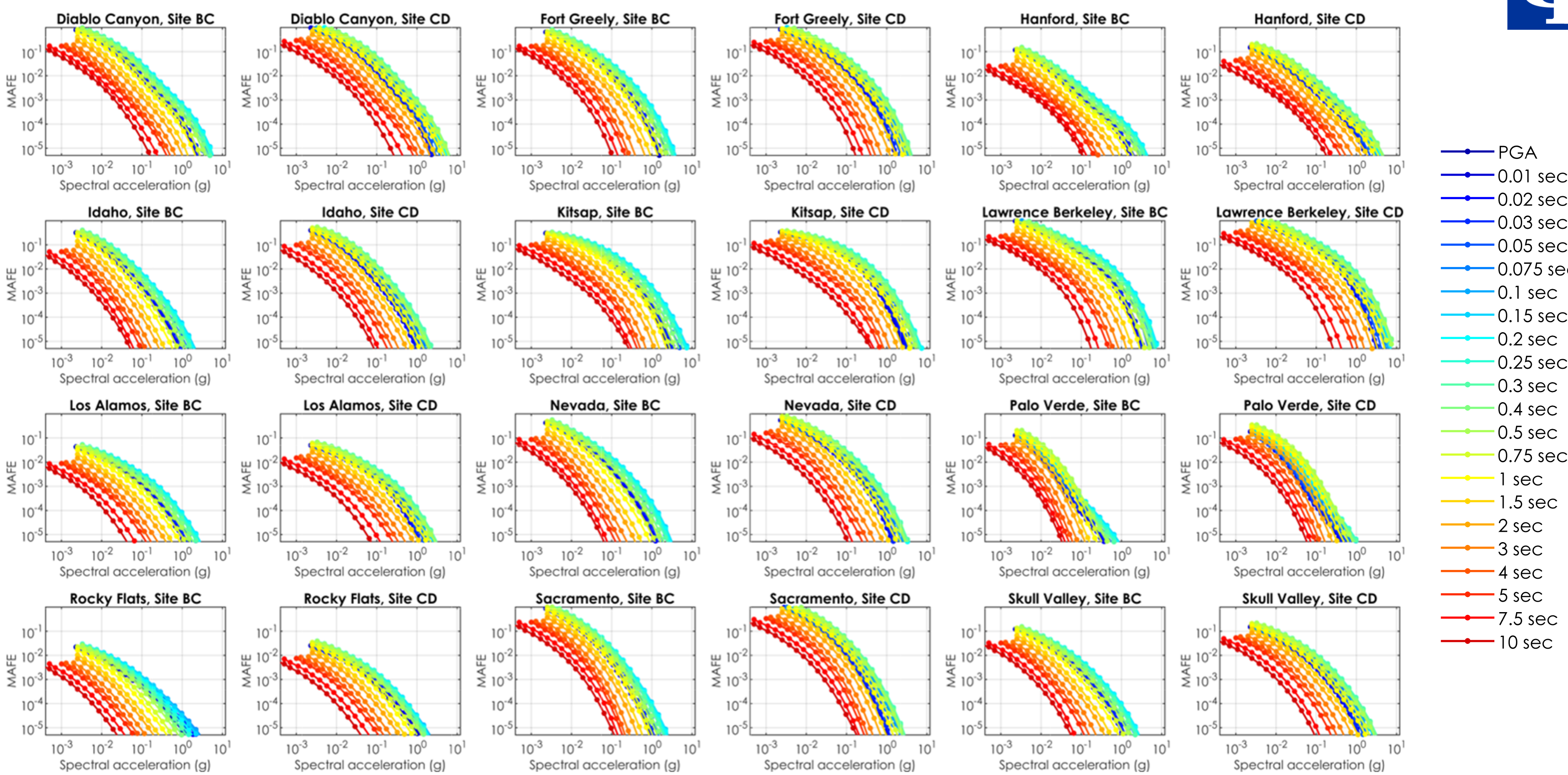
β for LS-D = 0.3

Characterize A_R: 24 sites, 2 soil types, 3 SDCs, 11 periods

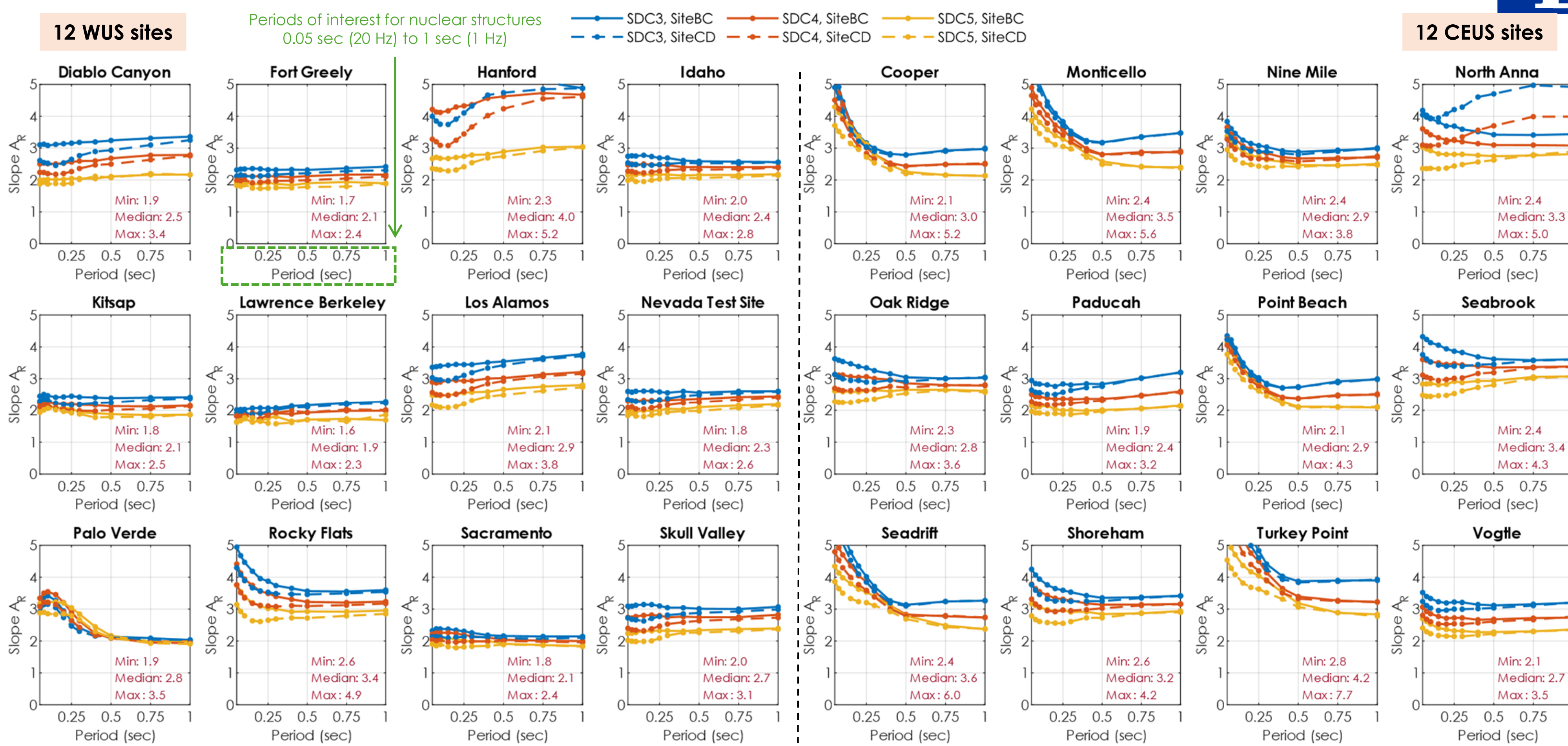


Group	#	Location	State	Latitude	Longitude
Western US	1	Diablo Canyon Nuclear Station	California	35.21	-120.85
	2	Fort Greely Nuclear Station	Alaska	63.95	-145.72
	3	Hanford Site	Washington	46.64	-119.59
	4	Idaho National Lab	Idaho	43.52	-112.98
	5	Kitsap Naval Base	Washington	47.65	-122.64
	6	Lawrence Berkeley Lab	California	37.87	-122.25
	7	Los Alamos National Lab	New Mexico	35.87	-106.32
	8	Nevada Test Site	Nevada	37.11	-116.05
	9	Palo Verde Nuclear Station	Arizona	33.38	-112.86
	10	Rocky Flats Plant	Colorado	39.88	-105.20
	11	Sacramento	California	38.58	-121.49
	12	Skull Valley Band	Utah	40.74	-112.69
Central and Eastern US	13	Cooper Nuclear Station	Nebraska	40.36	95.64
	14	Monticello Nuclear Station	Minnesota	45.33	-93.84
	15	Nine Mile Nuclear Station	New York	43.52	-76.41
	16	North Anna Nuclear Station	Virginia	38.06	-77.79
	17	Oak Ridge National Laboratory	Tennessee	35.93	-84.31
	18	Paducah Nuclear Station	Kentucky	37.08	-88.60
	19	Point Beach Nuclear Station	Wisconsin	44.28	-87.53
	20	Seabrook Station	New Hampshire	42.89	-70.85
	21	Seadrift	Texas	28.41	-96.71
	22	Shoreham Nuclear Station	New York	40.96	-72.86
	23	Turkey Point Nuclear Station	Florida	25.43	-80.32
	24	Vogtle Nuclear Station	Georgia	33.14	-81.76

Hazard curves: 12 western US sites (USGS hazard toolbox, 2023 data)

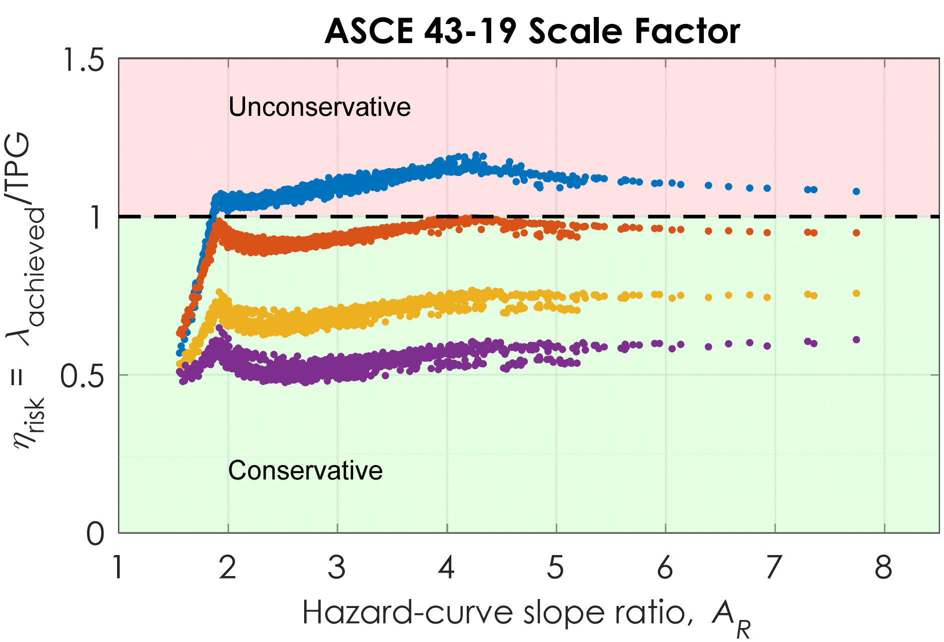


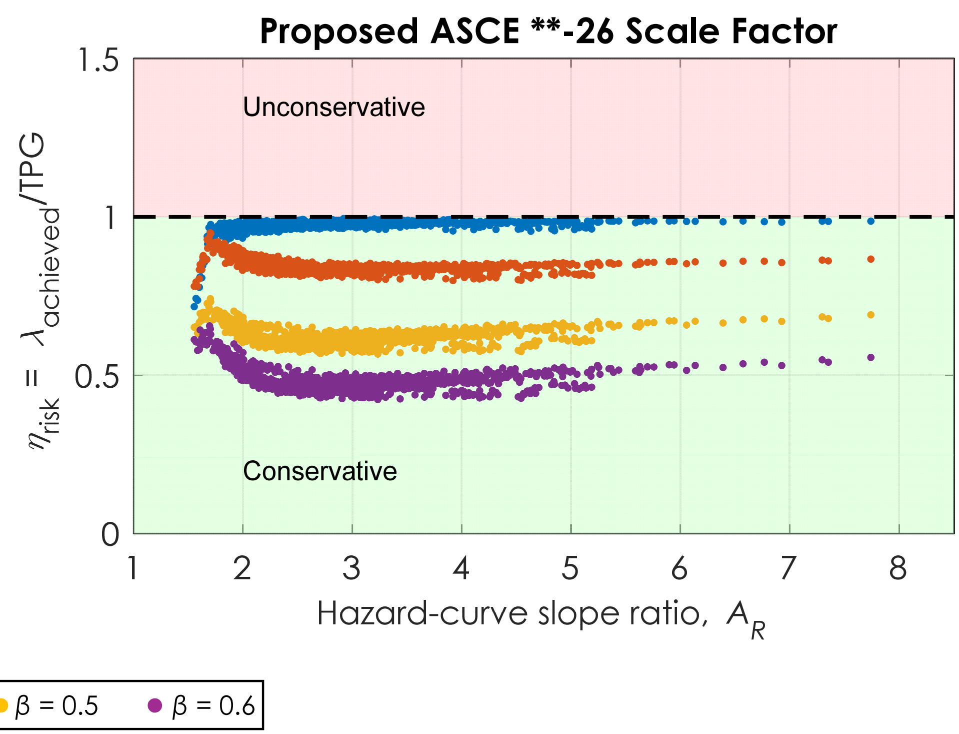
Seismic hazard slopes, 1584 A_R: 24 sites, 2 soil types, 3 SDCs, 11 periods



Risk performance: alternate DRS scale factors

DRS = UHRS * SF

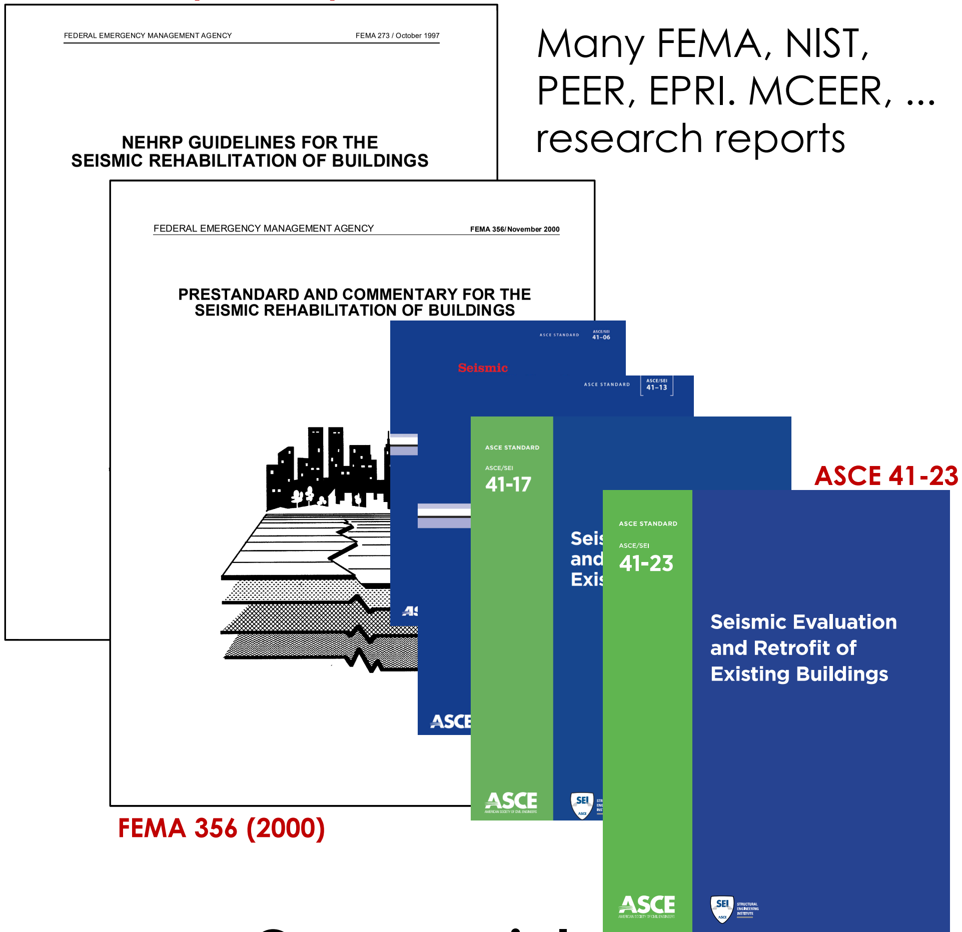




RIPB standards for commercial and nuclear civil structures

FEMA 273/274 (1992-1997)

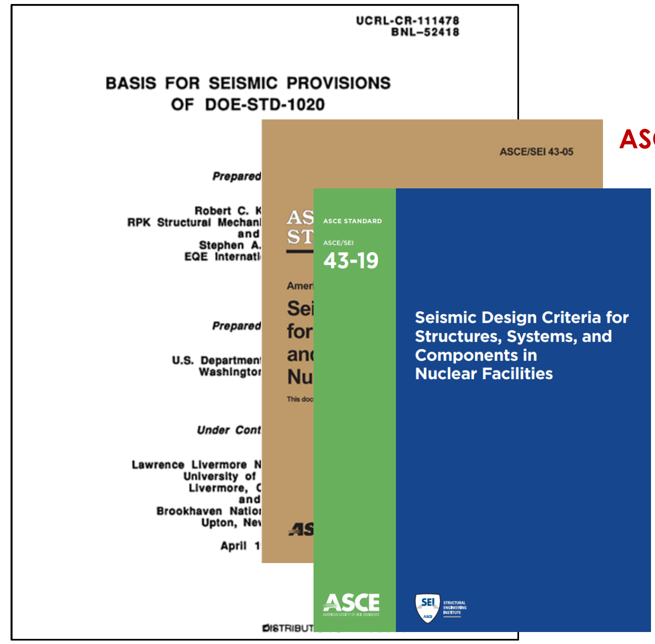
Many FEMA, NIST, PEER, EPRI. MCEER, … research reports



ASCE 41-23

FEMA 356 (2000)

Kennedy & Short 1994



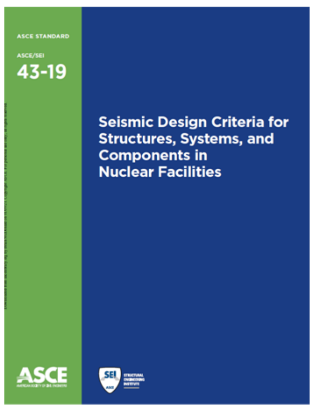
ASCE 43-05

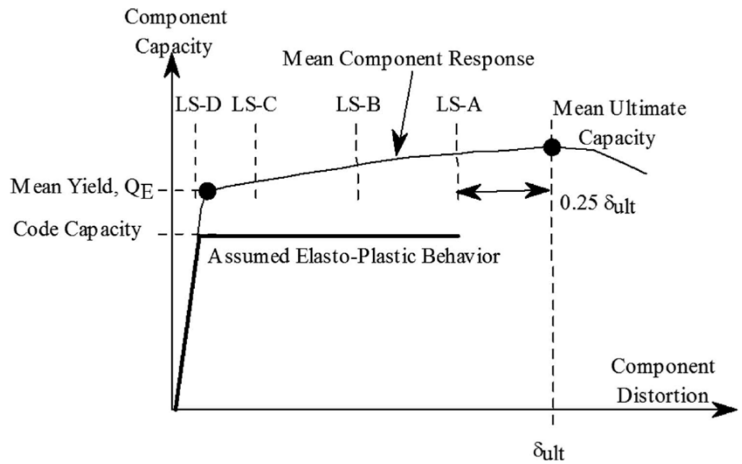
ASCE 43-19

Commercial **Nuclear**

Connecting some dots

Nuclear





Non-nuclear

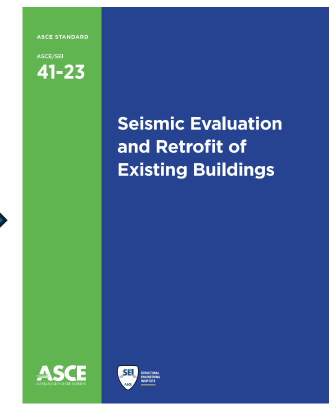
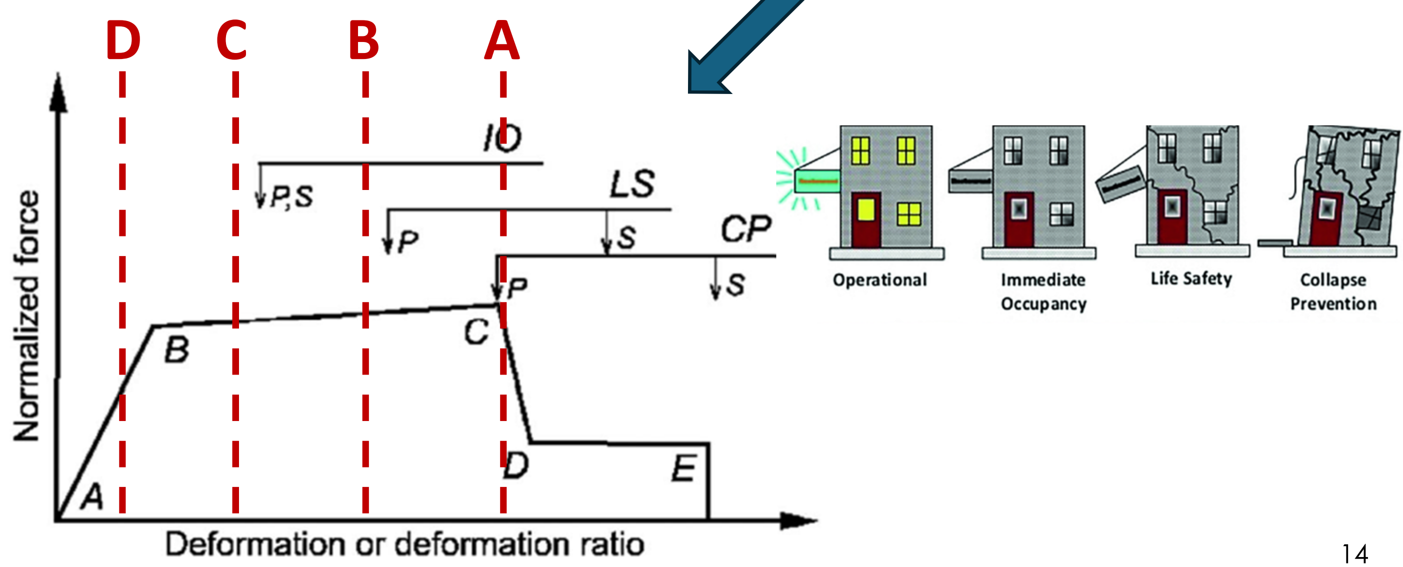


Table 1-2. Deformation and Damage by Limit State.

Limit State	Expected Deformation	Expected Damage
A	Large permanent distortion, short of collapse	Significant
B	Moderate permanent distortion	Generally repairable
C	Limited permanent distortion	Minimal
D	Essentially elastic behavior	Negligible

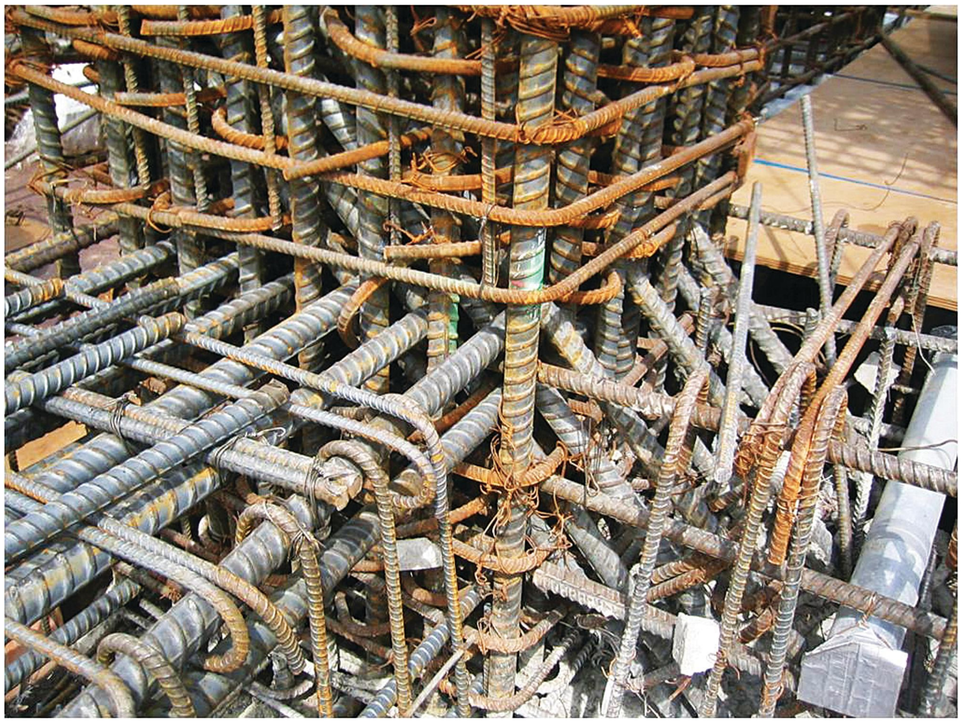
Source: Adapted from ANS 2.26 (ANS 2017).



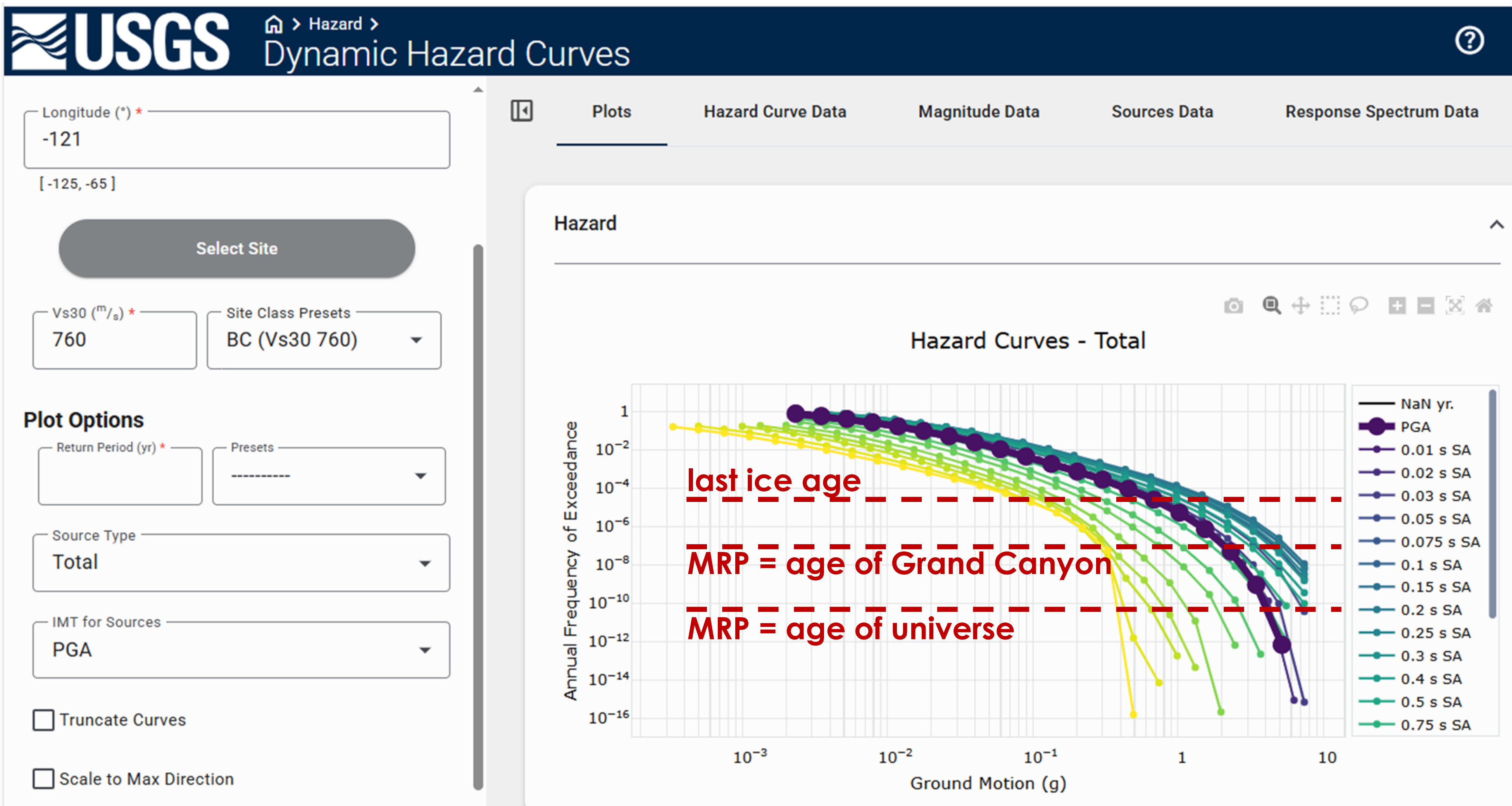
New acceptance criteria, NLRHA

- Recall Intent of ASCE 43-19
  - Target design fragility curve based on risk tolerance (**RI**)
  - Less than 1% chance of damage exceeding LS at DBE
  - Less than 10% chance of damage exceeding LS at 150% DBE
- Nonlinear structural analysis is now routine for commercial safety critical structures, and always required for commercial RIPB design
- To ballot a requirement to require RHA to demonstrate #3 is satisfied
  - Generate 11 representative ground motion triplets using standard tools
  - Allow damage LS to be exceeded for no more than one realization
    - Implemented at the component level
  - None of the simulations can exhibit instability

Quality assurance for high-performance civil structures



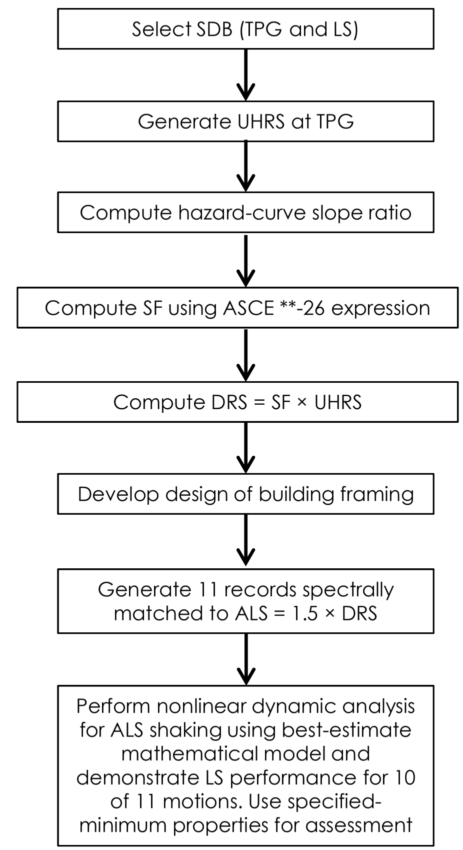
- Update Quality Assurance requirements to reflect civil structures, but meeting intent of 10 CFR Part 50 Appendix B


USGS
Hazard
Dynamic Hazard Curves
Longitude (°) *
-121
[-125, -65]
Select Site
Vs30 (m/s) *
760
Site Class Presets
BC (Vs30 760)
Plot Options
Return Period (yr) *
Presets

Source Type
Total
IMT for Sources
PGA
Truncate Curves
Scale to Max Direction
Plots
Hazard Curve Data
Magnitude Data
Sources Data
Response Spectrum Data
Hazard
Hazard Curves - Total
last ice age
MRP = age of Grand Canyon
MRP = age of universe
Annual Frequency of Exceedance
Ground Motion (g)
NaN yr.
PGA
0.01 s SA
0.02 s SA
0.03 s SA
0.05 s SA
0.075 s SA
0.1 s SA
0.15 s SA
0.2 s SA
0.25 s SA
0.3 s SA
0.4 s SA
0.5 s SA
0.75 s SA

Simplified pathway to RIPB proposed for ASCE **-26: September 2025

1. Select a Seismic Design Category (SDC) for an SSC, which defines the target performance goal (TPG), namely, a mean annual frequency of exceedance (MAFE) of a limit state
2. Select the damage limit state for the SSC
3. Generate seismic hazard curves for the site, with consideration of soil type (proxy is V_{s30}
4. Generate uniform hazard response spectrum (UHRS) at TPG for the chosen SDC: MAFE = TPG: SA_{TPG}
5. Compute hazard-curve slope ratio, A_R, using spectral acceleration at TPG and that at 10×TPG, namely, SA_{TPG} / SA_{10xTPG}, across the range of spectral periods of interest (e.g., 0.05 sec to 1 sec)
6. Compute scale factors (SF)* using the revised scale factor expression, period by period, and compute the largest value
7. Generate design response spectrum (DRS) using the largest SF from step 6 and UHRS of step 4
8. Develop a design for the framing system using the DRS in step 7, the ASCE 41-17 m-factors for the given limit state, and specified material properties. Check component capacities for all non-seismic load combinations
9. Generate 11 records of spectrally matched ground-motion triplets consistent with the assessment level spectrum (ALS), which is defined as 150% of the DRS
10. Develop a nonlinear mathematical model of the building of step 8 per ASCE 41. Perform linear or nonlinear response-history analysis, using the 11 sets of ground motions generated in step 9. Linear analysis is permitted for LS-D structures. Other limit states require nonlinear analysis. Ensure that the acceptance criteria per ASCE 41 for the chosen limit state are not exceeded for any component in at least 10 of the 11 analysis cases. Use specified properties for performance assessment. Adjust the design of components as needed



Send complaints to

mcdonald@exponent.com

Send compliments to

awhittak@buffalo.edu

sparsi@x-energy.com