



Risk-informed, performance-based design of seismic isolation systems for nuclear energy facilities

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Outline

- Risk integral
- Topical report to USNRC, May 2025
 - Seismic base isolation of reactor buildings
 - Isolation of equipment not explicitly addressed
 - Agnostic to reactor type and size, and isolation system
 - LLWRs, ARs, micros
 - 2D and 3D isolation systems
 - NRC audit underway
- Risk-informed performance-based design of an isolation system
 - Calculating D50: an evolution
 - Approach 1, Approach 3, Approach 4
- Sample calculations
- Closing remarks



Taylor Devices

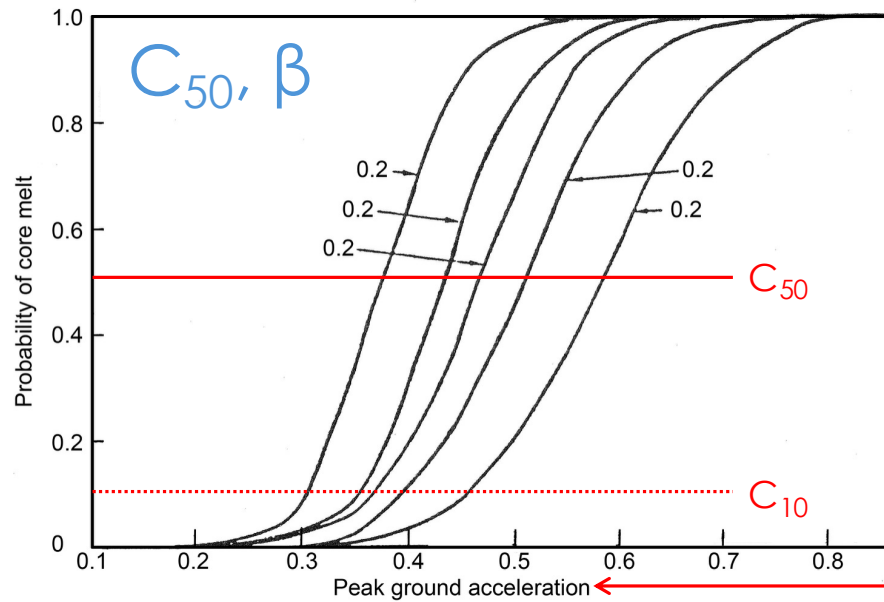


Risk integral: 1981, nuclear energy, Zion

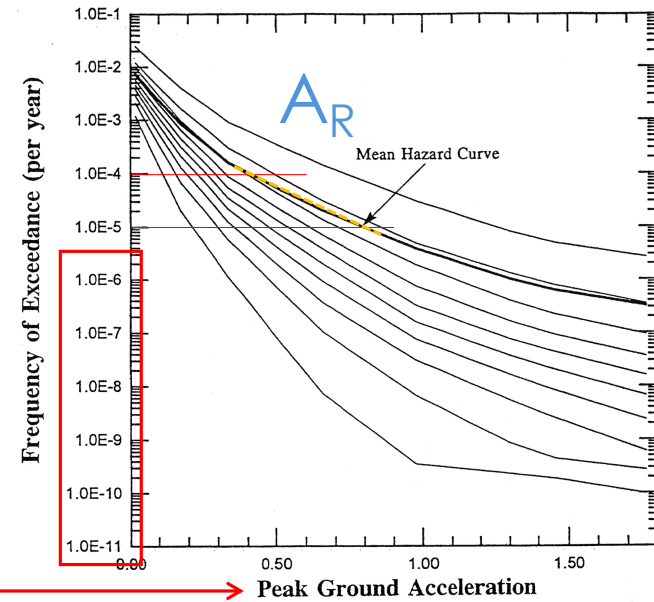
$$\lambda_f = - \int P_{f|a} \frac{d\lambda}{da} da$$

Risk
 C_{50}, β
 A_R

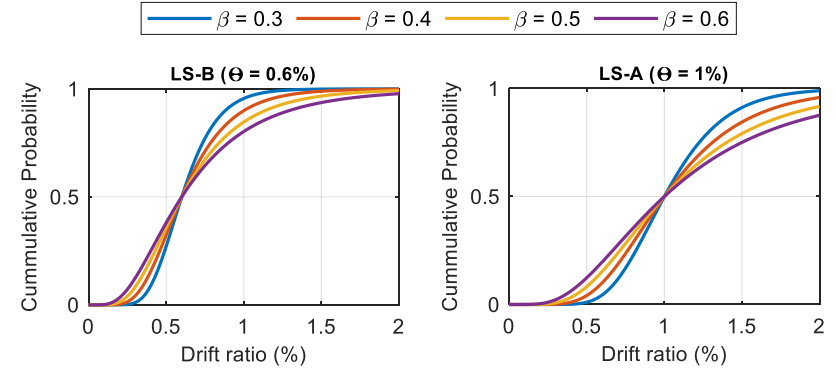
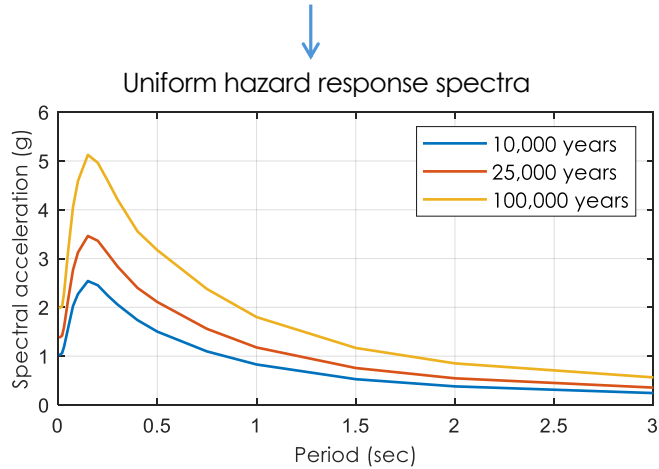
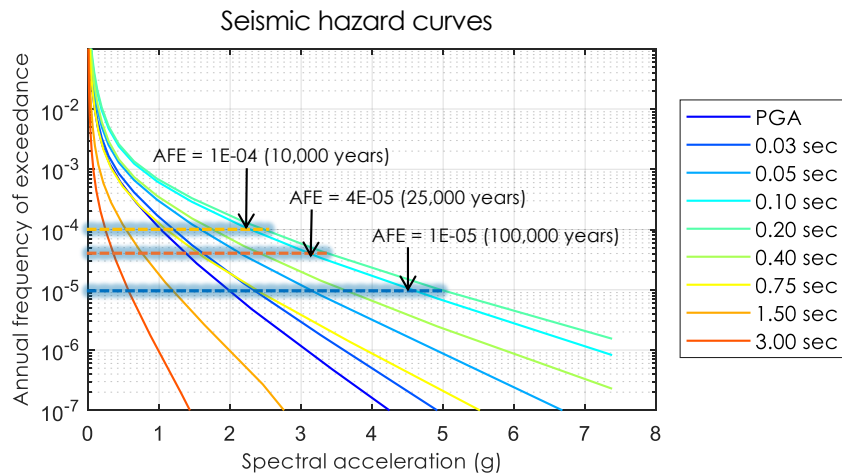
Pickard, Lowe, and Garrick, Inc, 1981



Pickard, Lowe, and Garrick, Inc, 1981



Risk integral: 2026, nuclear energy



Topical report on seismic isolation

- Achieving a **target performance goal, TPG, P_F**
 - Mean annual frequency of unacceptable performance
 - Isolation system (isolators + dampers) treated as an SSC
 - Traditionally defined by a **Seismic Design Category (SDC)**
 - SDC determined by seismic probabilistic risk assessment
 - Consequence of SSC failure
- TPG** delivered via prototype testing of devices for displacement D50
- Analysis, design, functional requirements
- Qualification, prototype, and production testing
- Specifications and commercial grade dedication

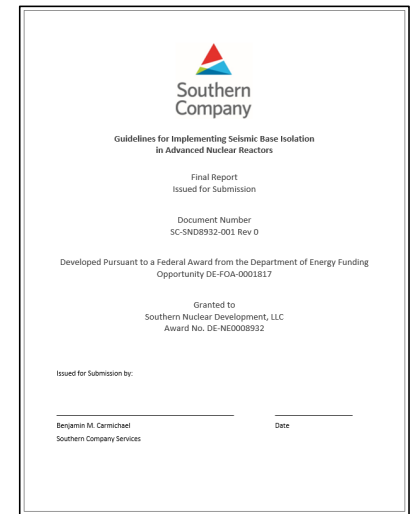
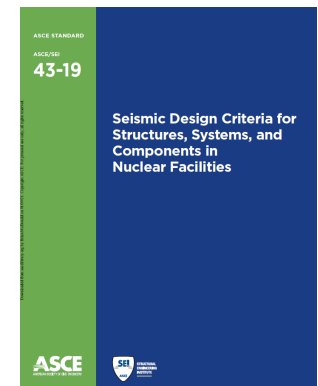


Table 1-1. Summary of Earthquake Design Provisions.

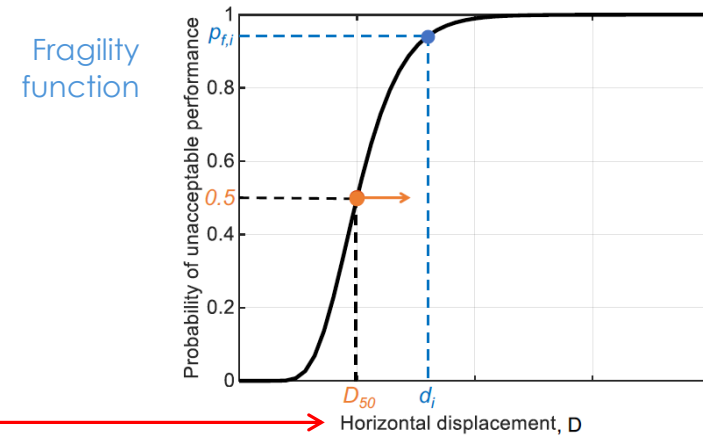
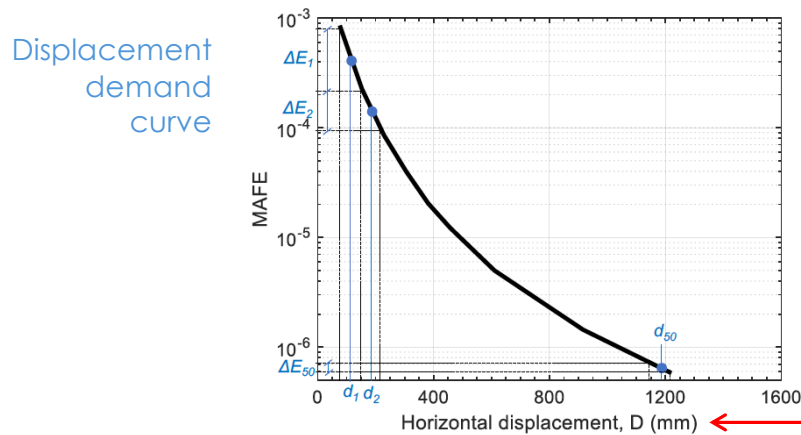
	Seismic Design Category			
	2	3	4	5
Target performance goal, P_F	4×10^{-4}	1×10^{-4}	4×10^{-5}	1×10^{-5}

DBE response spectrum or acceleration time series SF × UHRS; Chapter 2 in this standard



Achieving a TPG for an isolation system

- Unacceptable performance is what?
 - Insufficient **unrestricted horizontal displacement** capacity of the isolation system
 - Impact on adjacent construction is **unacceptable**
- Target performance goal is user specified, from an SPRA
- Fragility function demand parameter is **horizontal displacement**
 - Seismic hazard curves \longrightarrow displacement demand curve
- Approaches 1 and 3: numerically integrate to compute risk, iterate on D50 to achieve TPG

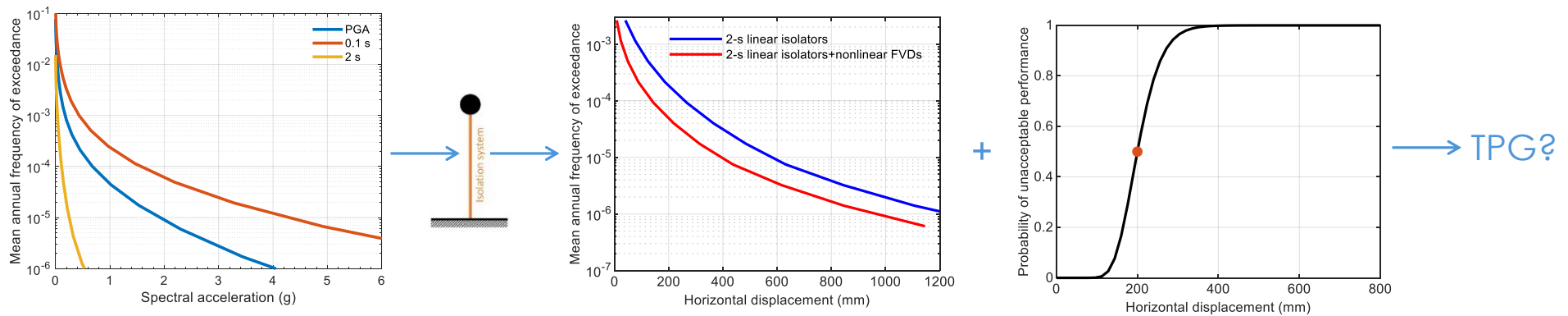


Treatment of uncertainty and variability

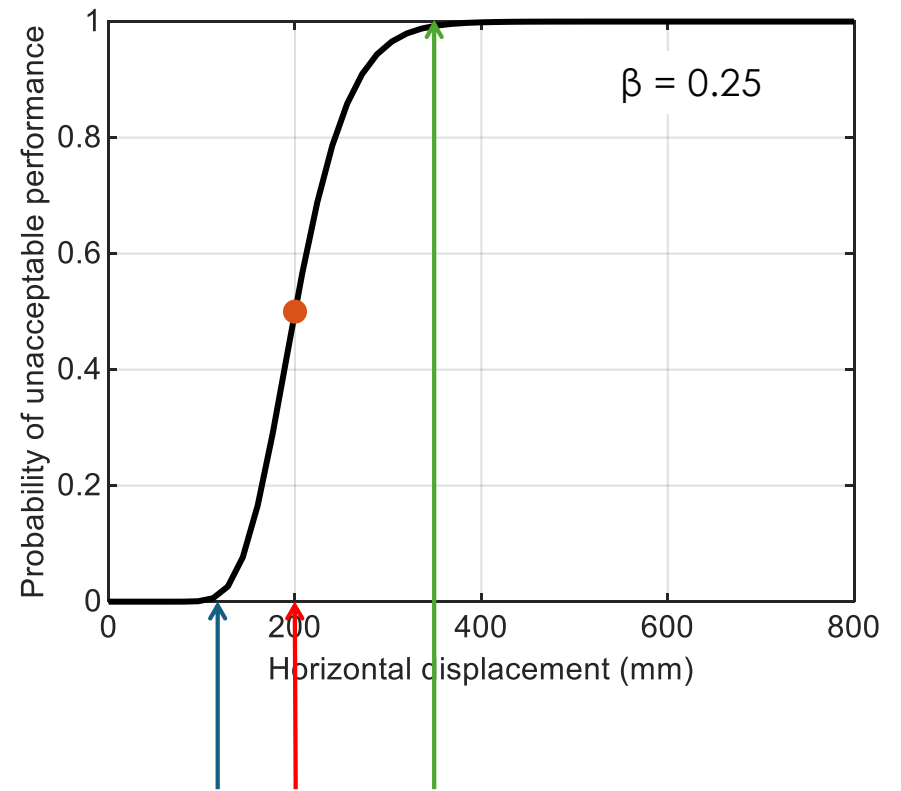
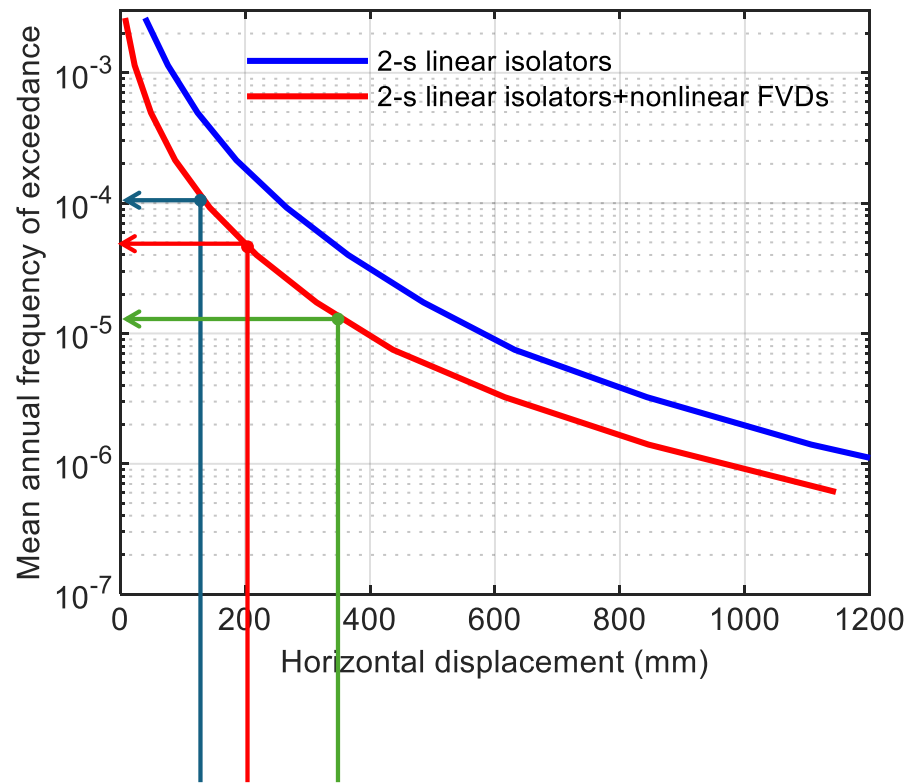
- Considered
 - Ground motion record-to-record (RTR)
 - Variability in displacement response for spectrally matched ground motions
 - Ground motion directionality: termed **maximum direction** in ASCE/SEI 7
 - Isolation system mechanical properties, $\beta_i = 0.05$
 - Mass distribution in the isolated nuclear power plant, $\beta_m = 0.05$
 - Model fidelity, $\beta_f = 0.05$
 - Isolation system **capacity**, $\beta_c = 0.05$
- Approach 1: industry standard approach, EPRI 2018
 - Displacement correction for effects of directionality
 - Uncertainty and variability addressed via the fragility function
- Approach 3
 - Ground motion RTR and directionality variability addressed via the demand curve
 - Other variabilities addressed via the fragility function

Generating a displacement demand curve: Approaches 1 and 3

- Seismic hazard curves from PSHA
- Nonlinear dynamic analysis of 2DOF model
 - 2DOF model sufficient to compute horizontal displacement
- 2DOF model unique to chosen isolation system
 - Vertical ground shaking? Not needed per Mosqueda *et al.* (2002)
- Displacement demand curve unique to site, soil, and isolation system

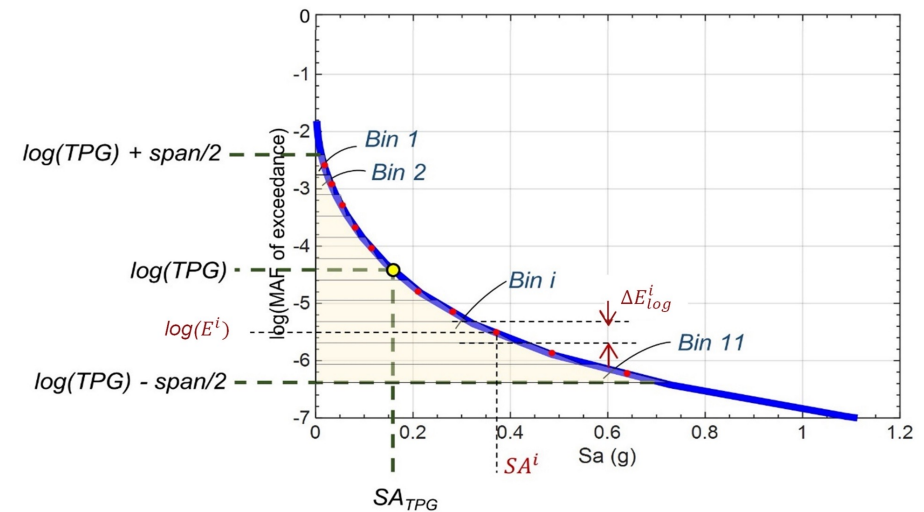


A minor, but relevant diversion



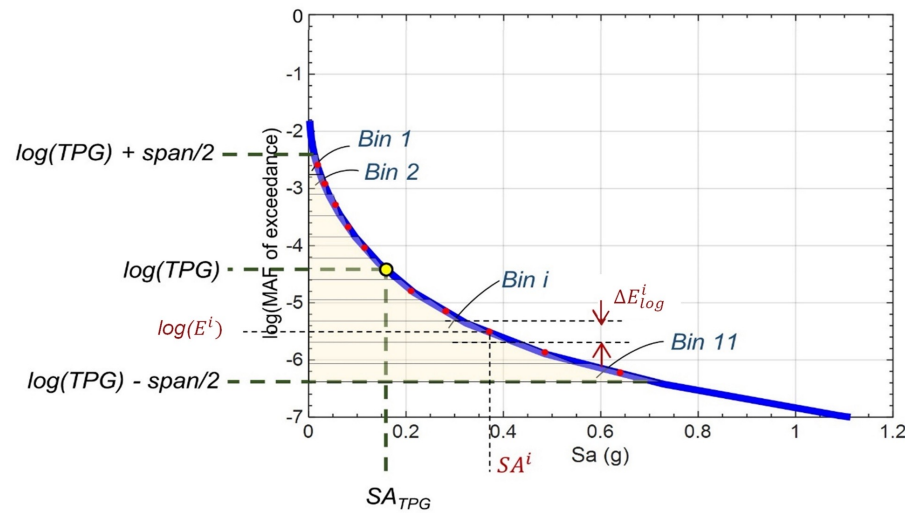
Achieving a TPG for an isolation system: Approach 1

- Displacement demand curve (DDC)
 - 11 bins spanning 4 decades in MAFE
 - Midpoint geomean UHRS in each bin
 - 11 pairs of matched motions per bin
 - Mean maximum displacement per bin
 - DDC generated using
 - 11 mean maximum displacements
 - Increased by 1.2 for directionality
- Fragility function to compute D50
 - Defined by D50 and a composite dispersion
 - Composite dispersion = SRSS of demand and capacity dispersion
 - Default = 0.35 for all isolation systems (smaller for linear systems)
 - Ground motion (RTR and directionality) dispersion dominates

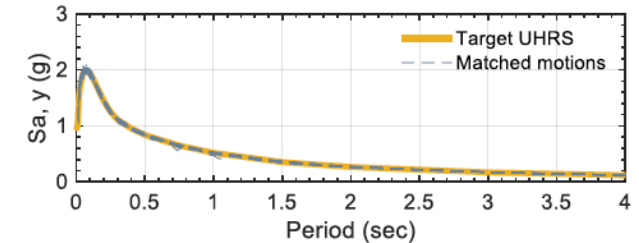
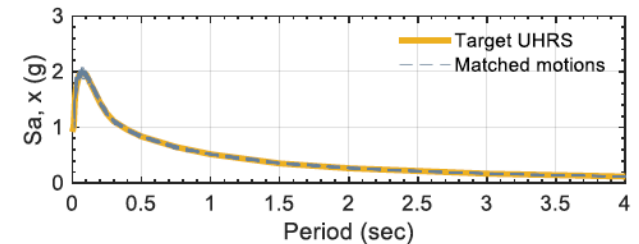


Exercising the process

- Clinch River Site, ORNL
 - Seismic hazard data per the USGS
 - Site classes: BC ($V_{s30}=760$ m/s) and CD ($V_{s30}=365$ m/s)
 - Eleven bins of earthquake shaking, spanning 4 decades
 - Thirty pairs of 2D ground motion time series per bin
 - Spectrally matched
 - 30 seed motions from the PEER database

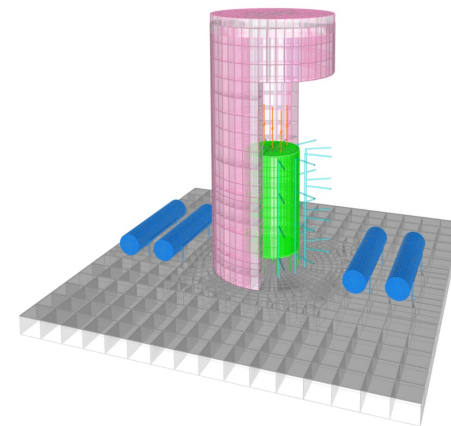
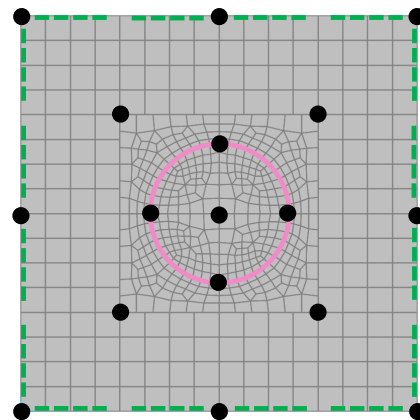
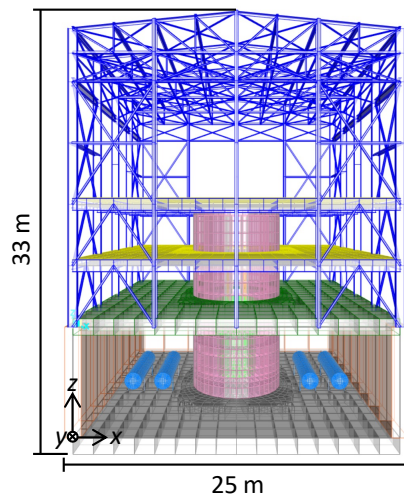


RP = 25,000 years
C/D
5% damping



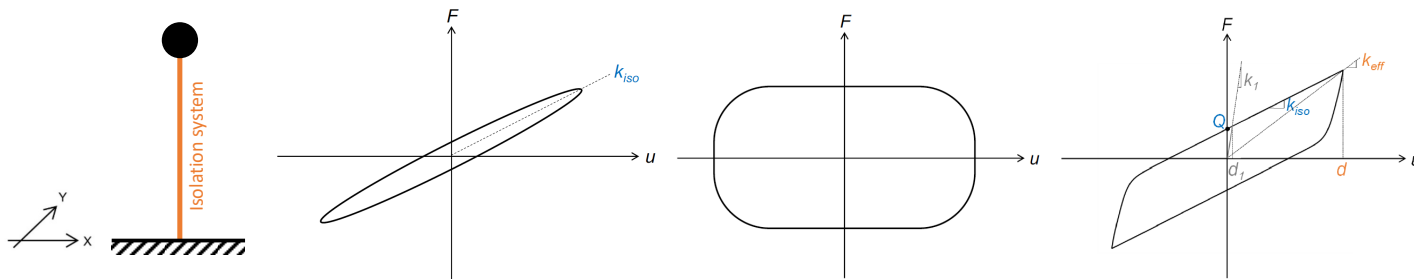
Exercising the process

- Archetype reactor building
 - Early version of the Kairos Power molten salt reactor
 - Selected safety-related SSCs included in the SAP2000 model
 - 17 isolators, locations not optimized; 1D FV dampers



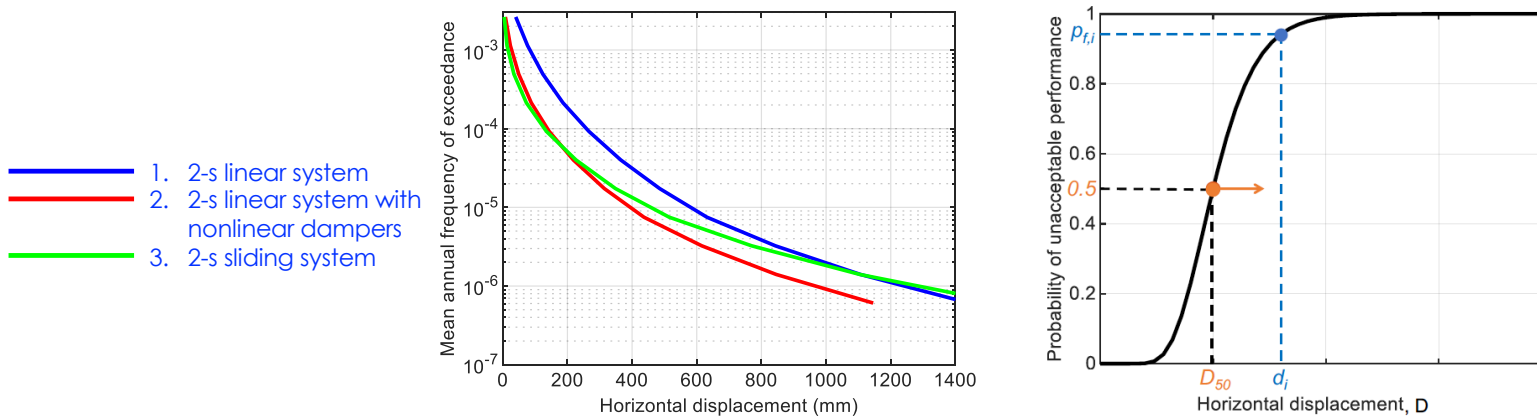
Exercising the process

- Isolation systems
 - 2D: 2s linear isolators, 2s linear isolators + nonlinear dampers, 2s single spherical sliding (bilinear) isolators, 2s bilinear isolators + 1D nonlinear fluid viscous dampers, 3s bilinear isolators
 - 3D: spring isolators (1.1 s H, 0.4 s V) + 3D viscoelastic dampers, hybrid isolation system (2 s H, 0.4 s V) + 1D fluid viscous dampers
- Linear and nonlinear dynamic analysis of 2DOF model using SAP2000



Exercising the process: Approach 1

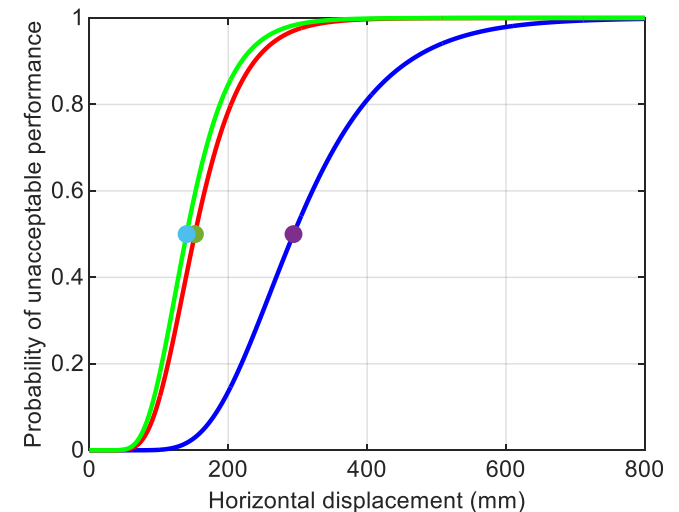
- Displacement demand curve
 - Nonlinear analysis, 11 *shaking* bins across 4 decades, 11 motions per bin, 121 analyses
 - 11 values of mean maximum displacement
 - Increase displacements by a factor of 1.2 to account for directionality: MCEER report
- Fragility function
 - $\beta=0.35$ for all sources of uncertainty and variability
 - Increment D50 to achieve the TPG



Exercising the process: Approach 1, constant TPG

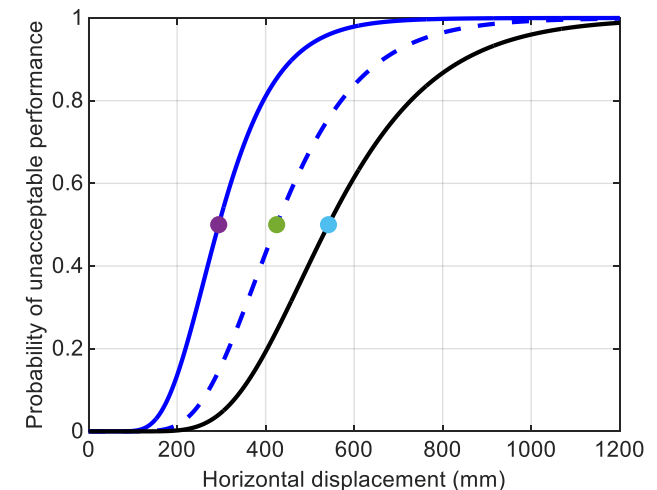
- Calculate D50
 - Basis for prototype testing
- Fragility function
 - Composite $\beta = 0.35$ dominated by ground motion; non-ground-motion $\beta = 0.10$
- Three isolation systems, TPG=E-4 (SDC 3), $\beta = 0.35$, CD soil
 - 2s linear isolators: D50 = 295 mm
 - 2s linear isolators + nonlinear dampers: D50 = 150 mm
 - 2s bilinear isolators: D50 = 140 mm

- 1. 2-s linear system
- 2. 2-s linear system with nonlinear dampers
- 3. 2-s bilinear system



Exercising the process: Approach 1, one isolation system

- Calculate D50
 - Basis for prototype testing
- Fragility function
 - Composite β dominated by ground motion; capacity $\beta_c = 0.05$
- Three TPGs, 2-second linear isolation system, $\beta = 0.35$, CD soil
 - D50 = 295 mm for TPG = E-4 (SDC 3)
 - D50 = 425 mm for TPG = 4E-5 (SDC 4)
 - D50 = 540 mm for TPG = E-5 (SDC 5)



Approach 3

- Developed to benchmark Approach 1
- Compare risk numbers and D50 for the two approaches
- Approach 1
 - Methodology consistent with EPRI 2018 (<https://www.epri.com/research/products/000000003002012994>)
 - Directionality addressed via factor of 1.2 on DDC determined using matched motions
 - Fragility function β addresses both demand (ground motion) and capacity
- Approach 3
 - Ground motion variability and directionality included in the demand curve
 - Dispersions: $\beta_i = 0.05$, $\beta_m = 0.05$, $\beta_f = 0.05$, $\beta_c = 0.05$
 - Composite $\beta = 0.10$ via SRSS of individual β_*

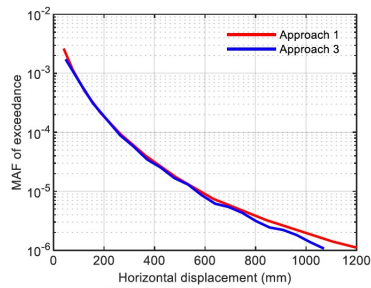
Approach 3

- Max-min motions for variability and directionality
 - Median = 1.3, log standard deviation = 0.13 (Huang *et al.* 2008)
 - Based on recorded ground motion time series
- Thirty sets of motions per bin, 11 bins spanning 4 decades
 - Spectrally matched motions in a pair scaled by F_h and $1/F_h$
 - Recovers the geomean UHRS in the bin
- DDC constructed using 330 values of maximum displacement, each associated with AFE

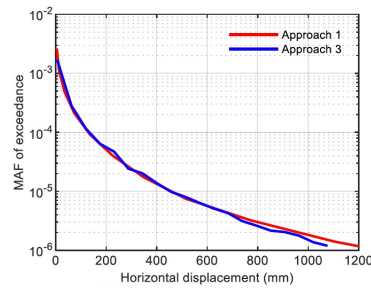
Table 1. Factors, F_h , randomly sampled from a lognormal distribution with a median of 1.3 and a log standard deviation of 0.13

1.182	1.540	1.090	1.606	1.174	1.389
1.531	1.473	1.016	1.294	1.197	1.402
1.274	1.297	1.055	1.116	1.146	1.422
1.607	1.378	1.283	1.249	1.461	1.557
1.371	1.013	1.142	1.390	1.414	1.190

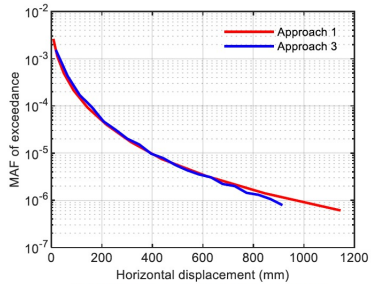
DDCs using Approaches 1 and 3, Clinch River, CD soil



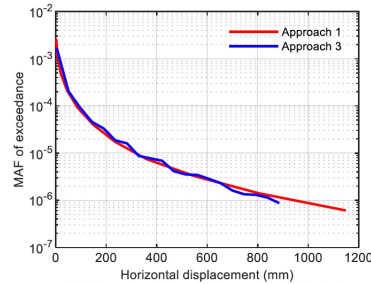
(a) 2-sec linear system



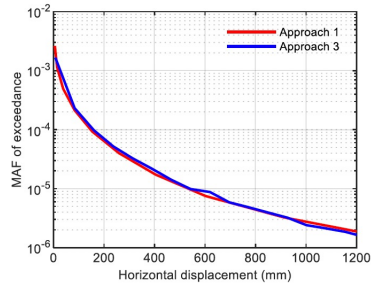
(b) 2-sec nonlinear system



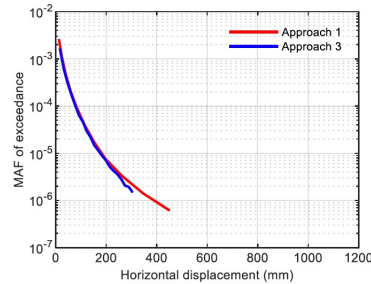
(c) 2-sec linear + nonlinear FVDs



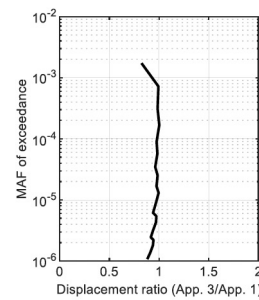
(d) 2-sec nonlinear + nonlinear FVDs



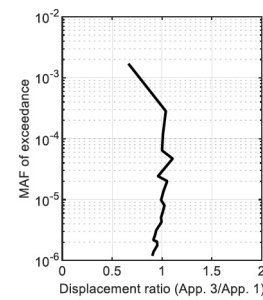
(e) 3-sec nonlinear



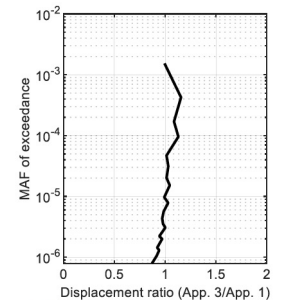
(f) 3D linear



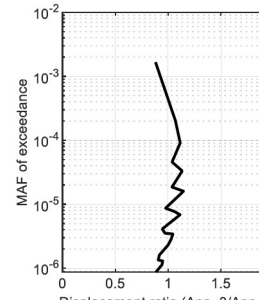
(a) 2-sec linear system



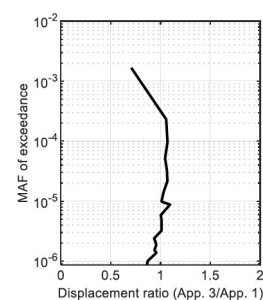
(b) 2-sec nonlinear



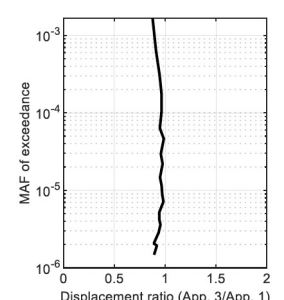
(c) 2-sec linear + nonlinear FVDs



(d) 2-sec nonlinear + nonlinear FVDs



(e) 3-sec nonlinear



(f) 3D linear

- DDCs from Approaches 1 and 3 are functionally identical

D50 calculated using Approaches 1 and 3, Clinch River, CD soil

Table 5. Median displacement capacity, D50, units of mm, to achieve different TPGs, Clinch River, CD soil, Approach 1: $\beta = 0.35$, Approach 3: $\beta = 0.1$

Isolation system		Target performance goal			
		1E-4	4E-5	2E-5	
1	2-sec linear system	Approach 1	294	424	542
		Approach 3	258	360	454
2	2-sec nonlinear system	Approach 1	140	248	360
		Approach 3	134	242	328
3	2-sec linear isolation system + nonlinear FVDs	Approach 1	152	244	334
		Approach 3	156	226	304
4	2-sec nonlinear system + nonlinear FVDs	Approach 1	90	162	240
		Approach 3	92	162	234
5	3-sec nonlinear system	Approach 1	160	284	416
		Approach 3	160	278	400
6	3D linear system, $T_{iso,h} = 1.1$ s	Approach 1	92	132	170
		Approach 3	80	112	140

- Use of computationally more expensive Approach 3 yields *identical* or lower D50 or MAFE of unacceptable performance

Approach 4: hot off the press

- Given the observations
 - Ordinates of DDC per Approach 1 \geq Approach 3 for a given MAFE
 - $\beta = 0.10$ for SRSS of non-ground-motion dispersions
 - For $\beta \leq 0.15$, nearly all the risk accrues in the decade below the TPG
 - DDC can be linearized in log space for a 10-fold change in MAFE: DR
 - Appendix A of ASCE/SEI 43-19 (RPK), replacing hazard curves by DDC

$$F_{50\%} = \exp\left(\frac{1}{2}K_H \beta^2\right)$$

$$K_H = \frac{1}{\log DR}$$

$$DR = \frac{DDC(@TPG)}{DDC(@10TPG)}$$

$$D(TPG) = D(@TPG) \times F_{50\%}$$

APPENDIX A
ALTERNATE METHOD TO MEET ASCE 43 PERFORMANCE GOALS WHEN SEISMIC CAPABILITIES ARE DEFINED AT THE 50% PROBABILITY OF FAILURE LEVEL

A1. INTRODUCTION

For some seismically induced failure modes (primarily soil failure modes), it is common engineering practice to define the seismic capability at the 50% probability of failure level (called herein *median capacity*, $C_{50\%}$) and to apply an appropriate factor of safety. This appendix defines an acceptable method to meet the ASCE 43 performance goals, P_F , when the seismic capability is defined at the median capacity level, $C_{50\%}$.

A2. SPECIFICATION OF THE DESIGN RESPONSE SPECTRUM

The design response spectrum (DRS) DRS_A , for use with median capacities is defined by

$$DRS_A = F_{50\%} \times UHRS_{H_p} \quad (A-1)$$

where $UHRS_{H_p}$ is the uniform hazard response spectrum defined at the mean annual frequency of exceedance $H_p = P_F$.

A3. SPECIFICATION OF MINIMUM FACTOR OF SAFETY TO BE APPLIED TO MEDIAN PROBABILITY OF FAILURE CAPABILITY

The minimum required factor of safety, $F_{50\%}$, to be applied to the median capacity, $C_{50\%}$, is defined by

$$F_{50\%} = \exp\left[\frac{1}{2}K_H \beta^2\right] \quad (A-2)$$

where β defines the natural logarithmic standard deviation of the capacity, and

$$K_H = \frac{1}{\log A_R} \quad (A-3)$$

where A_R is defined in Section 2.2 of the standard. Because $F_{50\%}$ is particularly sensitive to β , either a realistic or conservative estimate of β shall be made.

Approach 4: hot off the press

- $D50 = DDC(@TPG) * F50\%$
 - $F50\% = f(\beta, DR)$
 - For $1.5 < DR < 10$, $\beta \leq 0.10$, $F50\% < 1.03 \approx 1.0$
- Compute D50: DDC replaced by a demand point
 - 11 sets of motions matched to UHRS at $MAFE = TPG$ (derivative of Approach 1)
 - Increase mean of 11 max displacements by 1.20 (directionality = 1.2 with $F50\% = 1.0$)

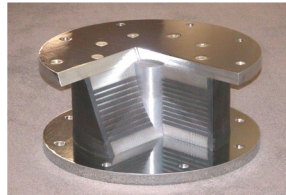
Table 12. Median displacement capacity, $D(TPG)$ in mm, to achieve different TPGs, Clinch River, CD soil, $\beta = 0.10$

Isolation system		TPG							
		1E-4		4E-5		2E-5		1E-5	
		1) ¹	2) ¹	1)	2)	1)	2)	1)	2)
1	2-sec linear	262	262	370	369	468	471	580	590
2	2-sec sliding	130	130	228	228	326	330	450	462
3	2-sec linear + nonlinear FVDs	140	139	220	220	298	301	390	399
4	2-sec sliding + nonlinear FVDs	84	83	150	150	220	222	310	319
5	3-sec sliding	150	148	262	261	378	382	524	539
6	3D linear, $T = 1.1$ s	82	82	116	116	146	148	182	185

1. 1) = displacement computed by integration; 2) displacement associated with F50%

Closing remarks

- Topical report to support the implementation of base isolation
- Process demonstrated to achieve a TPG for an isolation system
 - Performance calculation: fragility function + displacement demand (curve/point)
 - Displacement demand curve: isolation-system, site/geology specific
 - Fragility functions: median capacity and β
 - Determine minimum median displacement capacity, $D50 = D(TPG)$
- Evolution: Approach 1 through Approach 4
- Results benchmarked
- D50 used for prototype testing to confirm TPG will be achieved





Acknowledgements

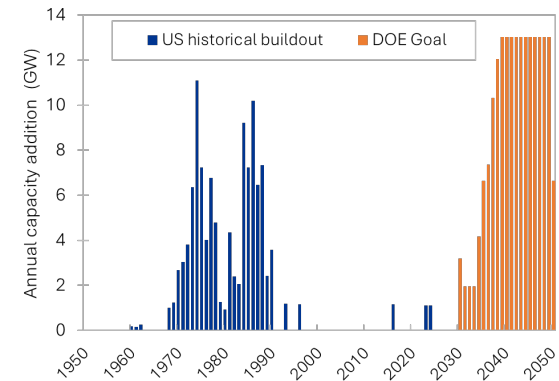
UB and IIT Jammu: Faizan Mir

Southern Company: Brandon Chisholm

SGH: Mohamed Talaat



W. Robbie Stewart (Alva) and DOE LPO



Malhotra and Schmidt (Joule, 2020)

