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RISK-INFORMED DISPLACEMENT CRITERIA FOR DESIGNING SEISMIC ISOLATION SYSTEMS WITHOUT A STOP

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ABSTRACT

The Licensing Modernization Project (LMP) put forth by the Nuclear Energy Institute (2019) presents a risk-informed performance-based (RIPB) licensing framework for non-light water reactors. Separately, Lal et al. (2022), Parsi et al. (2022), Yu et al. (2018), and others have identified the cost benefits of implementing seismic base isolation in nuclear power plants. Together, these two considerations encourage advanced reactor developers to explore the process of implementing RIPB design for seismic isolation (SI) systems. Doing so requires explicitly treating the entire hazard range, not only the design basis level with margin. Novel approaches are needed since the response of SI systems is governed by displacement, whereas standard equipment is acceleration-controlled. One method to limit displacement is by designing a stop; this approach requires characterizing the seismic demands on isolated SSCs upon impacting the stop. This post-impact demand characterization is not always straightforward, which incentivizes understanding the displacement threshold needed for which impacting a stop does not meaningfully influence facility risk insights. Accordingly, this paper outlines a process for developing RIPB SI displacement thresholds and illustrates how this can affect the design of an SI system.

We summarize an approach that defines the required SI displacement capacity to achieve desired risk targets without relying on a seismic stop. The method considers the entire range of applicable seismic hazards and does not require pre-determination of design-basis or beyond-design-basis earthquake levels. When followed, the strategy outlined herein determines the SI system displacement capacity, which would not significantly contribute to overall facility risk if exceeded. Here, the capacity is a probabilistic characterization, such as one for convolving with hazard, rather than an SSC qualification capacity at a design basis level. The displacement criteria, then, is informed by a risk threshold to ensure displacement-induced failure is not risk-significant.

Typically, seismic probabilistic risk assessments (SPRAs) convolve acceleration-based seismic hazards or demands with acceleration-based seismic fragilities to estimate the risk over an acceleration range. However, the risk convolution can operate with any ground motion intensity measure. The methodology presented here performs the convolution using the displacement demand at pre-determined SI frequencies. The SI frequency is a project-specific design parameter selected by the design team. An analytical model of the isolated SSC, including SI at target frequencies, is then analyzed at a range of seismic hazard levels. The analysis results in terms of maximum SI displacements are then used to develop the displacement demand curves capturing a range of earthquake annual frequencies of exceedance (AFE) and the corresponding SI displacements at those AFE.

The displacement demand curve is then used in risk convolution to identify the required displacement-based seismic fragility of the SI needed to achieve the specified risk target. The resulting median and high confidence of a low probability of failure (HCLPF) capacity represent displacement threshold criteria. The design team can progress with designing the SI system and related features using the identified RIPB displacement thresholds. Additionally, one can develop testing criteria to achieve the target isolator capacity, including the displacement amplitudes, required number of tests, and test success criteria.

This information is necessary for isolator vendors to understand the system requirements completely. Lastly, one can map the displacement-based seismic fragility back to accelerations for use in the SPRA to support the LMP process.

The paper provides examples of implementing the approach using two sites/seismic hazards, two SI system frequencies, and three assumed target performance goals.

INTRODUCTION

A seismic isolation system (SIS) reduces the acceleration of isolated SSCs by concentrating deformation in the isolator units. This acceleration reduction is a primary driver for incorporating an SIS in a nuclear application because it reduces in-structure seismic demands for the isolated SSCs. Furthermore, incorporating an SIS permits design organizations to pursue a standardized plant design by designing SSCs once and adjusting the SIS design to suit the selected site's seismological environment. The cost benefits of implementing a SIS in nuclear power plants are addressed further in Lal et al. (2022), Parsi et al. (2022), Yu et al. (2018), and others.

Here, we first demonstrate the benefits of an SIS on in-structure seismic demands and then focus on the SIS deformation and the resulting displacement of isolated SSCs, which is a function of the SI frequency. Defining SIS displacement criteria, including a displacement threshold, is, therefore, a function of SI frequency, and increasing the stiffness of the SIS can mitigate cases when a displacement threshold is too large to tolerate for a given isolated SSC.

The decisions to use an SIS in the first place and whether to include an engineered stop are partly driven by - and sensitive to - the site's seismic hazard. For example, we corroborate the intuition that Central and Eastern United States (CEUS) sites with low amplitude low-frequency hazards are generally more suitable for excluding a stop than Western US (WUS) sites with meaningful low-frequency amplitudes.

Motivation

Once an organization decides to pursue an SIS for its facility, the distance between the isolated SSCs and adjacent construction becomes a natural consideration. If the organization also plans to use a risk-informed licensing strategy like the LMP (NEI, 2019), the next step in the natural progression would be to risk-inform that necessary clearance.

The risk-informed process typically involves a probabilistic risk assessment (PRA) for internal and external events, and the SIS primarily contributes to the SPRA. With these tools, the organization can assign overall plant risk targets, which the SIS design team can use to determine the deformation threshold (or displacement capacity) needed to achieve those targets while accounting for the entire seismic hazard range (not limiting design to deterministic Design Basis Earthquake and Beyond Design Basis Earthquake).

Objective

When determining a risk-informed SI displacement threshold, the goal is to identify the displacement capacity that, if exceeded, would not significantly contribute to overall facility risk. This displacement capacity could be (a) impacting a designed stop (hard or soft), (b) impacting an adjacent SSC, (c) exceeding umbilical flexibility, or (d) exceeding isolator stability. The preference is to avoid impact (i.e., avoid (a) and (b)) because such an impact necessitates characterizing the loads on the impacting SSCs and assessing the consequences for the SPRA. Typically, this characterization involves nonlinear dynamic analysis, complicated seismic fragility evaluations, and other labor-intensive engineering assessments, which owners prefer to avoid when not necessitated by risk insights.

APPROACH

Traditional SPRAs convolve an acceleration-based seismic hazard with an acceleration-based seismic fragility to estimate a facility's risk over a range of ground motion accelerations. Peak ground acceleration (PGA) is often used for acceleration-based computations out of convenience. However, performing an SPRA does not require using acceleration; an analyst can use any ground motion intensity measure (IM) to complete the risk convolution, a concept illustrated in Figure 1. Yu et al. (2022) present a method for using displacement as the IM.

This paper further pursues the method of convolving seismic risk using displacement at two particular spectral frequencies, corresponding to distinct SI options: 0.5 Hz (a reasonable frequency, for, say, a lead-rubber bearing SIS) and 1.25 Hz (reasonable for spring-based SIS) horizontal This paper illustrates the approach for the horizontal direction only, but a similar approach could be implemented for the vertical direction if 3D isolation is used. This displacement-based risk convolution is achieved by exercising analytical models of a hypothetical base-isolated small modular reactor (SMR) building at a single point on the acceleration-based seismic hazard curve and scaling the results (neglecting for simplicity (i) potential effects of spectral shape with changing hazard levels, and (ii) isolator nonlinearity with increasing displacements, which may warrant consideration in commercial practice). The analytical model of the hypothetical SMR building includes SI with properties tuned to the target frequencies and idealized as linear. The hazard curves are site-specific for two sites, one in the Central and Eastern US (CEUS) and one in the Western US (WUS).

Through the analyses, we obtain and scale the building response to construct displacement demand hazard curves capturing a range of earthquake annual exceedance frequencies (AEF) and corresponding expected SI displacements at those AEF. Conservatively, we treat exceeding the specified displacement threshold as system failure, a conventional first step to avoid the labor-intensive analytical evaluations mentioned previously but a possible candidate for refinement if the risk results are intolerable. Additionally, we assess the condition where a building adjacent to the hypothetical SMR building (or its moat wall, if including a stop) can be sufficiently far away such that impact does not occur. In other words, we have not included abrupt failure modes with steep fragility curves to represent impact after the isolator reaches a stop. Lastly, we include an inherent assumption that the consequence of a single isolator becoming unstable before it reaches the specified displacement threshold leads to an unacceptable performance.

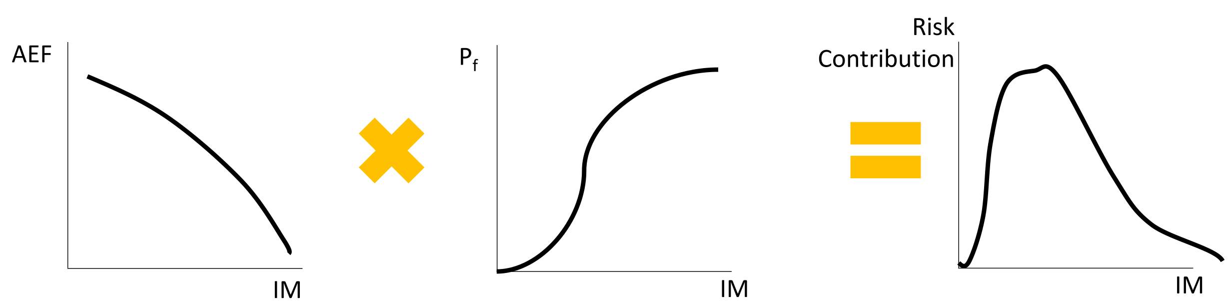

Figure 1. Idealized Seismic Risk Convolution. The ground motion intensity measure (IM) is often acceleration-based but can also be displacement-based at a selected frequency.

HYPOTHETICAL SMR BUILDING

The hypothetical SMR building is 80 ft x 80 ft in plan and 50 ft tall. There is one intermediate slab at half-height and a central cavity below the mid-height slab that is 35 ft x 35 ft in plan. The basemat (i.e., floating slab) is 5 feet thick, the roof and intermediate slabs are 3 feet thick, and the walls are 2 feet thick.

Penetrations in the walls and slabs allow for commodity crossings and access. We applied a uniformly distributed 1000 kip mass to the top of the central cavity representing an SMR and accounted for nominal additional permanent equipment loads throughout the building. Figure 2 shows a cutaway view of the analysis model used for demand analyses (discussed below) of the hypothetical SMR building.

We considered two cases for the SIS: 0.5 Hz and 1.25 Hz horizontal fundamental frequency. In both cases, we assigned 15% horizontal damping and 5% vertical damping, which could be achieved with single-device viscous dampers simultaneously in three directions or appropriately oriented linear/axial single-direction dampers.

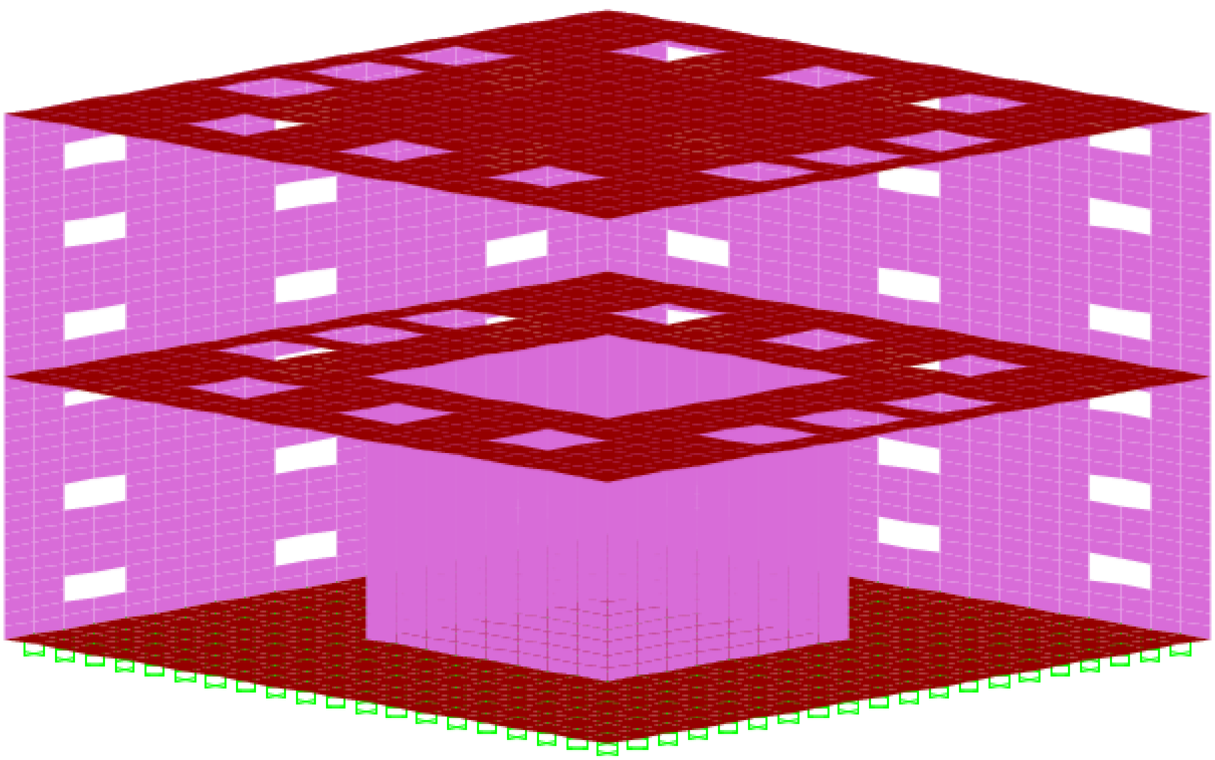

Figure 2. Isometric Cut-away View (Two Near Walls Hidden) of the Analysis Model of a Hypothetical Base-Isolated SMR Building

TARGET PERFORMANCE GOALS

An owner must decide the appropriate risk target for developing displacement criteria. They could make this determination using the Frequency-Consequence (F-C) plot from the LMP (NEI, 2019), ASCE 43 (2019) Table 1-1, or any number of other possible factors. Yu et al. (2022) point out that SIS performance must be at least that of isolated SSCs.

Herein, we use three distinct target performance goals (TPGs) to illustrate (a) the process of obtaining risk-informed displacement criteria and (b) the sensitivity of the displacement criteria to this selection: 1E-05, 1E-06, and 1E-07 annual frequency of unacceptable performance per year.

SEISMIC HAZARD

We select two locations to demonstrate the process of developing risk-informed displacement criteria. Figure 3 shows the seismic hazard curves obtained from the USGS Unified Hazard Tool (https://earthquake.usgs.gov/hazards/interactive/) using the Dynamic Conterminous U.S. 2014 Edition and Site Class B/C, and the ASCE 7 (2022) design response spectra for a risk category IV structure:

- A CEUS location: 600 Galleria Parkway, Atlanta, GA (33.884636, -84.461317)
- A WUS location: 4695 MacArthur Court, Newport Beach, CA (33.670409, -117.862139)

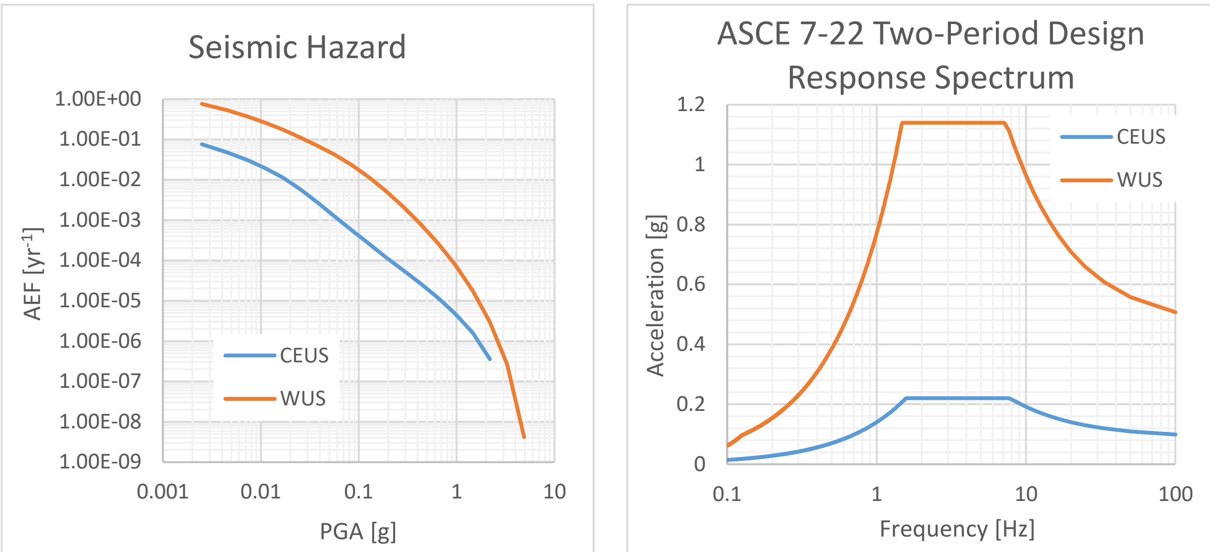

Figure 3. Seismic hazard from USGS (left) and design response spectra (right) for CEUS and WUS sites.

The ASCE 7-22 design response spectra are used as the target spectra for selecting time histories for analysis. With these target spectra, we obtain five (5) time histories from each site from the PEER Ground Motion Database and determine scale factors at several points along the PGA hazard curve. Each time history identified in Table 1 is linearly scaled to the DRS's PGA. Figure 4 shows the normalized response spectra and their average.

Table 1: CEUS and WUS Time Histories Used for Analysis (from PEER Ground Motion Database).

Earthquake Name	**Date**	**Recording Station**
	CEUS	
Whiting	2010-03-02	Hickman_ KY
MtCarmel	2008-04-18	Halls_ TN
RiviereDuLoup	2005-03-06	St-Roch-des-Aulnaies_ QC
AuSableForks	2002-04-20	Bruce Peninsula_ ON
ValDesBois	2010-06-23	Alfred_ ON
	WUS	
Borrego Mtn	1968	San Onofre – So Cal Edison
Lytle Creek	1970	Wrightwood – 6074 Park Dr
San Fernando	1971	Whittier Narrows Dam
Managua_ Nicaragua-01	1972	Managua_ ESSO
Northern Calif-07	1975	Cape Mendocino

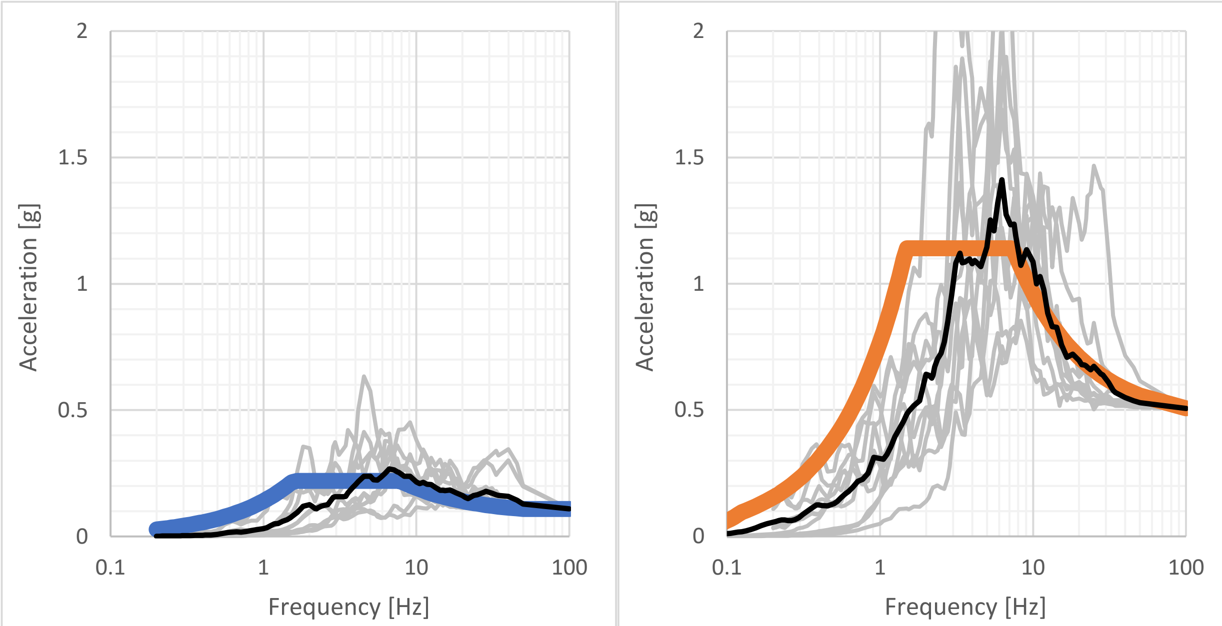

Figure 4. Scaled two horizontal component response spectra of selected earthquakes and their respective averages normalized to the Target Spectrum PGA for CEUS (left) and WUS (right).

DEMAND ANALYSIS

We analyzed the hypothetical SMR building using time-history response analysis for the five earthquake time histories mentioned above. Figure 5 compares the averaged in-structure response spectra (ISRS) at the top of the reactor cavity for the two SIS-frequency cases and the unisolated building for the CEUS and WUS motions and two horizontal directions. Figure 6 illustrates the corresponding displacement hazard curves constructed using the average of each time history's maximum building displacement output.

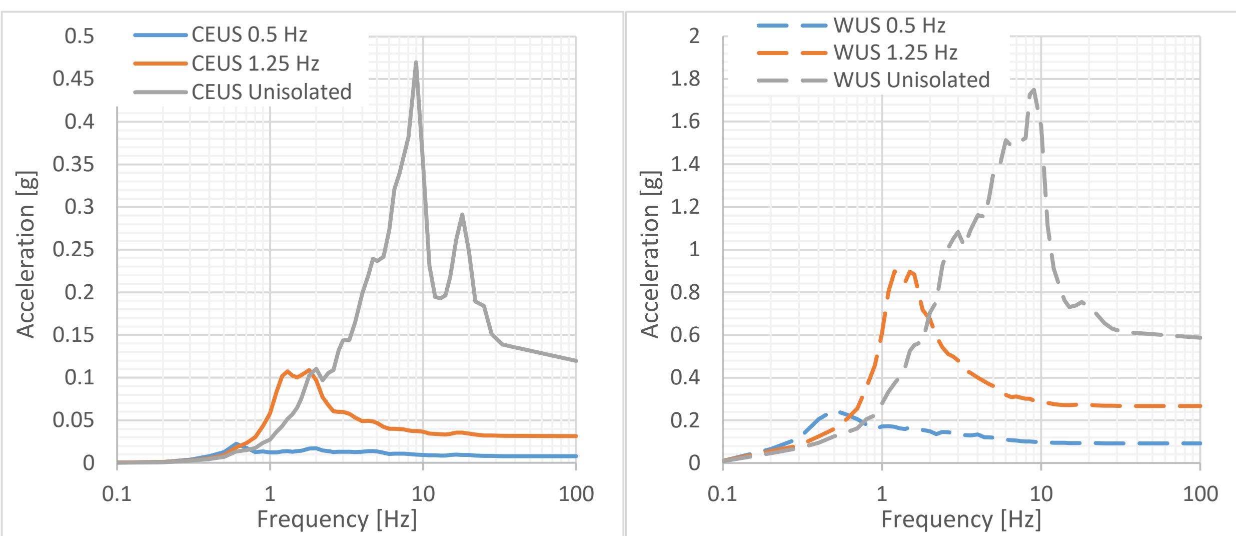

Figure 5. Comparison of the averaged 5% damped ISRS for the two SIS cases (0.5 Hz & 1.25 Hz) and an unisolated structure for CEUS (left) and WUS (right) at the Design Response Spectra Level.

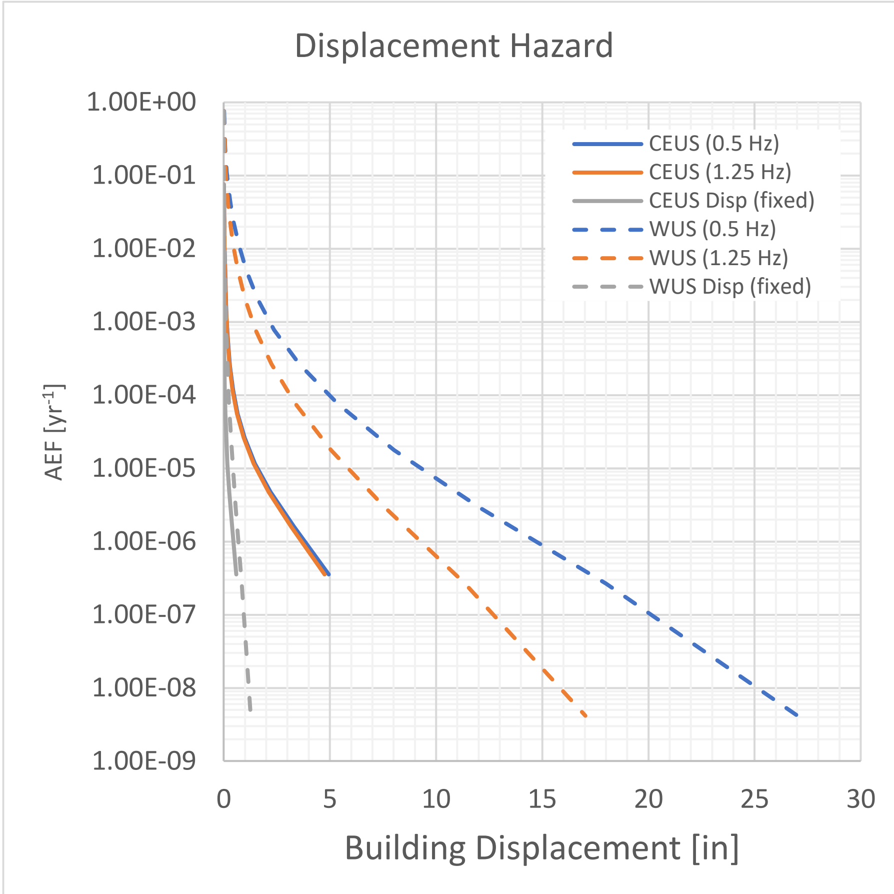

Figure 6. Displacement hazard curves for the averaged maximum building displacements for two SIS cases (0.5 Hz & 1.25 Hz) and an unisolated structure for CEUS and WUS.

SEISMIC FRAGILITY AND MEAN POINT RISK CONVOLUTION

By rearranging the mathematical expression of Figure 1, we use the displacement hazard curves shown for the isolated cases in Figure 6 to determine the displacement-based seismic fragility parameters to achieve the TPGs specified above as 1E-05, 1E-06, and 1E-07 per year. We perform this computation for each site and isolator frequency. The fragility is defined by a capacity term and its variability.

Variability

Composite variability, β_C, is considered as 0.39, per Equation 1. It consists of randomness in horizontal direction peak response, a small aleatory component reflecting variation between individual isolators, and more significant epistemic components attributed to structural response and isolator capacity.

β_{R_I}	= 0.05	Randomness for isolator-to-isolator differences
β_{R_GM}	= 0.13	Ground motion peak direction randomness, EPRI (2018) Section 5.4.1.2
β_{U_SR}	= 0.3	Structural response uncertainty
β_{U_SC}	= 0.2	Isolator capacity uncertainty

$$\beta_C = \sqrt{\beta_{R\_I}^2 + \beta_{R\_GM}^2 + \beta_{U\_SR}^2 + \beta_{U\_SC}^2} = 0.39 \tag{1}$$

Risk Convolution

Figure 7 shows each case's cumulative risk plot for each TPG, displacement hazard, and required fragility.

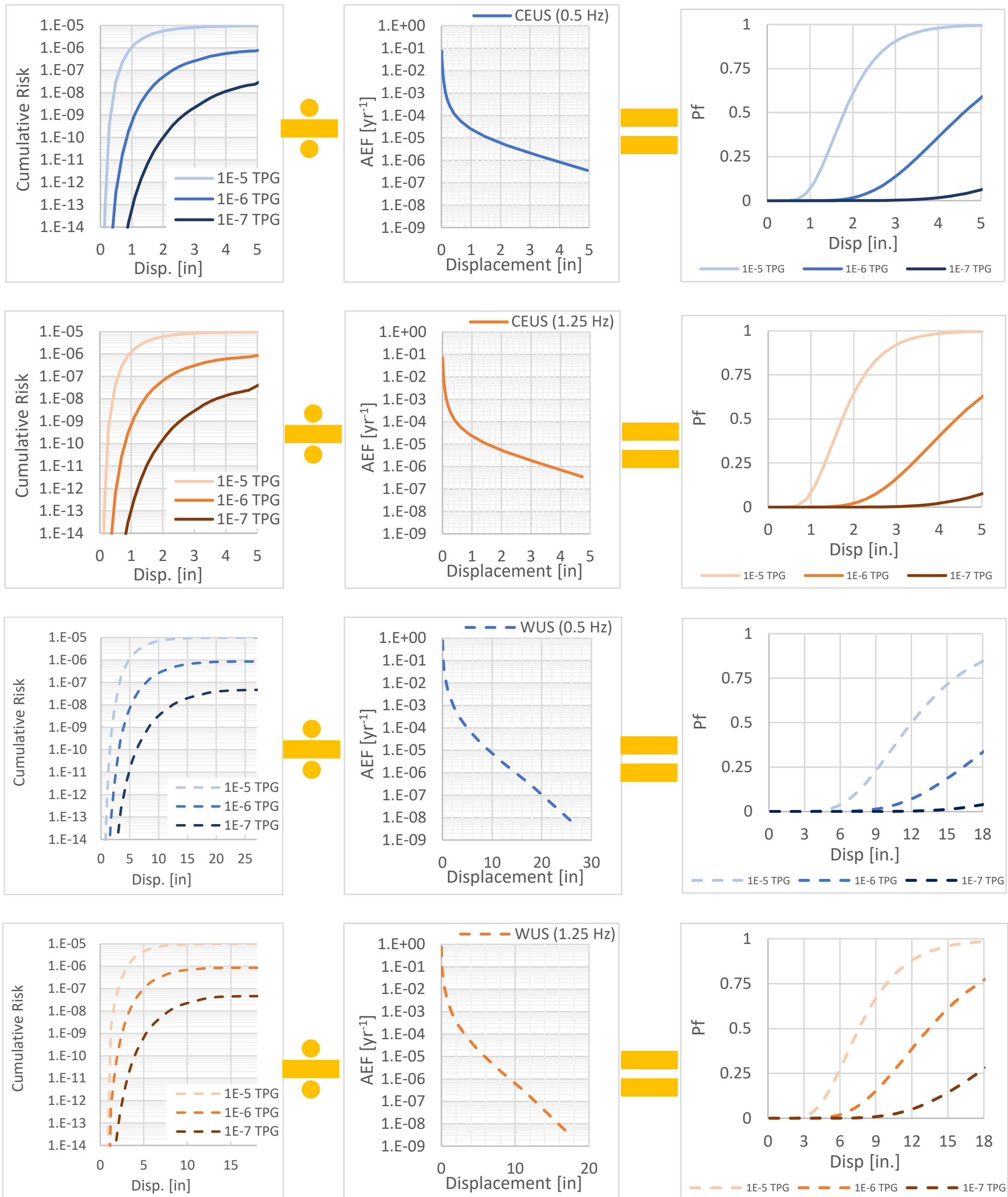

Figure 7. Risk Convolution for each site, SI case, and Target Performance Goal

RESULTS SUMMARY

Table 2 summarizes the minimum displacement capacity distributions to achieve the specified TPG. Median values indicate the 50-percentile displacement capacity, and HCLPF columns indicate the 1% non-exceedance probability displacement capacity.

Table 2: Minimum Displacement Capacity Distributions to Achieve Target Performance Goals.

TPG & SI Case	**Median [in]**		**HCLPF [in]**	
	CEUS	WUS	CEUS	WUS
1.0E-05				
0.5 Hz	1.80	12.03	0.73	4.85
1.25 Hz	1.73	7.59	0.70	3.06
1.0E-06				
0.5 Hz	4.6	21.3	1.85	8.58
1.25 Hz	4.41	13.43	1.78	5.41
1.0E-07				
0.5 Hz	9.17	36.05	3.70	14.53
1.25 Hz	8.79	22.75	3.54	9.17

As mentioned, traditional SPRAs usually convolve an acceleration-based seismic hazard and fragility using PGA as a convenient earthquake intensity measure. The displacements listed in Table 2 can be mapped to the PGA at the site through AEF to facilitate integration with traditional PGA-based SPRAs. Table 3 shows the PGA values corresponding to the displacements in Table 2; these represent the required fragility parameters, in terms of PGA, to achieve each TPG.

Table 3: PGAs mapped from displacements through AEF

TPG	**Median [g]**		**HCLPF [g]**	
	CEUS	WUS	CEUS	WUS
1.0E-05	0.8	2.2	0.3	0.9
1.0E-06	2.1	3.9	0.9	1.7
1.0E-07	4.0	6.0	1.8	2.6

DISCUSSION AND OBSERVATIONS

This paper demonstrates a risk-informed process for defining displacement criteria for a seismic isolation system without a stop. For a hypothetical SMR building in a CEUS and WUS site, we first illustrate the benefit of including an SIS by comparing ISRS for two different SIS frequencies to an unisolated building. Then, we develop displacement demand curves for the isolated cases and determine the required SIS fragility to achieve three different TPGs. In doing so, it is clear that the CEUS site is better suited for a seismic isolation system without a stop. This observation is intuitive since the CEUS site has low energy in the low-frequency range compared to the WUS site. The implication is that for WUS sites, it is challenging to design an SIS without implementing a stop because the isolators would require large displacement capacities not to be top seismic risk contributors. The same observation is evident from examining the acceleration-based fragility parameters: achieving the specified capacities would be challenging.

If reasonably achievable, avoiding impact with a seismic stop is desirable because if impact occurs, then one must assess the consequences of that impact, which almost certainly includes nonlinear analysis. Such nonlinear analysis introduces additional uncertainties, and while not necessarily overly complex or costly, the analyses in question would not be required for the design basis earthquake (where the stop would not be impacted) but only to support the SPRA for the beyond design basis hazard levels.

CONCLUSIONS

This paper presents a methodology to develop risk-informed displacement criteria for designing a seismic isolation system without a stop. It identifies minimum displacement capacities for an SIS to achieve a pre-defined risk target. The approach involves convolving displacement-based seismic hazard curves and fragilities iteratively to identify seismic fragility parameters to meet a specified TPG.

We develop a hypothetical base-isolated SMR building and perform a series of analyses to build displacement demand hazard curves as a function of SIS frequency for a CEUS site in Georgia and a WUS site in California. The process demonstrates that the CEUS site has more manageable displacement criteria than the WUS site, making it better suited for designing an isolation system without a stop using the risk-informed process.

Once complete, the design teams could use the displacement criteria to determine the test criteria needed to achieve the target SI displacement capacity reliably. In turn, the team could identify the displacement amplitude (based on appropriate variability) and the required number of tests, success criteria, and amplitude for writing a design specification.

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