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SEISMIC RISK ASSESSMENT FOR ISOLATED NUCLEAR POWER PLANTS: THE IMPLICATIONS OF A STOP

Manish Kumar[1], and Andrew S. Whittaker[2]

[1]Assistant Professor, Department of Civil Engineering, Indian Institute of Technology Gandhinagar, India; formerly graduate student, University at Buffalo, Buffalo, NY, USA.
[2]Professor, Department of Civil, Structural and Environmental Engineering, University at Buffalo, Buffalo, NY, USA; Director, MCEER.

ABSTRACT

Nuclear power plants (NPPs) are designed and assessed for severe earthquake shaking, which can pose significant demands on the structural system and internal equipment. Base isolation is a viable means to substantially reduce seismic risk. In the United States, isolation systems will comprise seismic bearings designed and tested to maintain the axial load carrying capacity with a 90+% confidence at the 90th percentile displacement for beyond design basis (BDB) shaking, where BDB shaking is linked to a uniform hazard response spectrum with a return period of 100,000 years. The earthquake risk is conservatively quantified herein in terms of annual frequency of unacceptable performance of an individual isolator, which provides a metric to compare the three risk-reduction strategies, namely, 1) testing prototype isolators to achieve higher confidence than 90%, 2) testing isolators to a greater displacement and corresponding axial load, and 3) providing a stop at the 90th percentile displacement for BDB shaking. Testing the isolators to 90% confidence at the 90th percentile BDB displacement results in a risk significantly smaller than 1×10^{-6} if the isolation system is complemented by a stop. Increasing either the confidence level and/or the displacement for prototype testing may not reduce risk to less than 1×10^{-6}.

INTRODUCTION

Figure 1 is a cross section through an isolated generic nuclear power plant (NPP), identifying the isolation system, the (hard) stop, and the isolated superstructure. Although there have been more than 10,000 applications of seismic isolation technology in the world to buildings, bridges and infrastructure, the applications to nuclear facilities are few in number. In the United States, the main impediments to the use of seismic isolation in nuclear facilities have been: 1) the small number of new build NPPs, and 2) a lack of regulatory guidance. The forthcoming NUREG entitled "Technical considerations for seismic isolation of nuclear facilities" (Kammerer et al. (forthcoming)) and Chapter 12 of ASCE 4-16 (ASCE 2016) address the second impediment by providing guidance on analysis and design of seismically isolated NPPs (NUREG) and Department of Energy facilities (ASCE 4-16), and on testing of prototype and production isolators.

This paper presents a study on the seismic risk associated with an isolation system in an NPP, and so utilizes the draft guidance in the NUREG. Seismic risk is quantified in terms of mean annual frequency of unacceptable performance of the isolation system. The effects of 1) testing isolators to achieve greater confidence in capacity, 2) testing isolators for a greater displacements and axial loads, and 3) providing a stop (physical restraint) at the 90th percentile displacement for beyond design basis shaking (a return period of 100,000 years per the NUREG) on the risk associated with failure of the isolation system are studied. Calculations are performed at sites of eight nuclear facilities in the United States to enable broad conclusions to be reached.

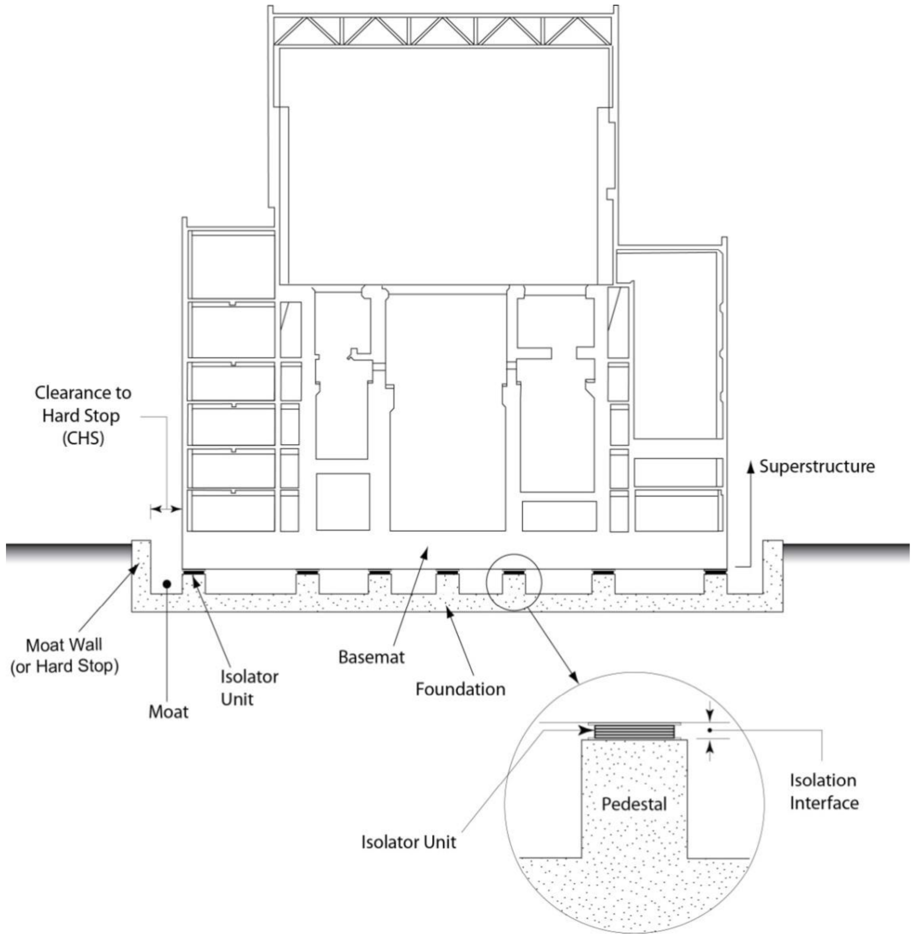

Figure 1. Schematic of a seismically isolated nuclear power plant (adopted from Kammerer et al. (forthcoming)).

SEISMIC HAZARD AT THE SITES OF NUCLEAR FACILITIES IN THE UNITED STATES

Figure 2 presents the seismic hazard (spectral acceleration plotted against annual frequency of exceedance) at eight sites of nuclear facilities in the United States (see Figure 3) for two periods, 1 s and 2 s[1], 5% damping, and a shear wave velocity in the upper 30 m of the soil column of 760 m/s. The data are obtained from http://geohazards.usgs.gov/hazardtool/application.php (accessed, December 30, 2014).

SEISMIC HAZARD DEFINITION FOR ISOLATED NUCLEAR POWER PLANTS

Two levels of seismic hazard are defined for seismically isolated NPPs per Kammerer et al. (forthcoming): 1) ground motion response spectrum+ (GMRS+), and 2) beyond design basis (BDB) GMRS. Ground motion response spectrum is the product of a design factor and a uniform hazard response spectrum (UHRS) with a mean annual frequency of exceedance (MAFE) of 10^{-4}. The design factor can be set equal to 1.0 for isolated NPPs (see Kumar et al. (2015, 2017)). The GMRS+ is the envelope of the GMRS and a regulator-specific minimum response spectrum (e.g., an appropriate spectral

[1]Periods of 1 s and 2 s are relevant for seismic isolation systems.

shape anchored to a peak ground acceleration of 0.1 g). The proposed beyond design basis GMRS is the greater of the UHRS with an MAFE of 10^{-5} and 167% of the GMRS+.

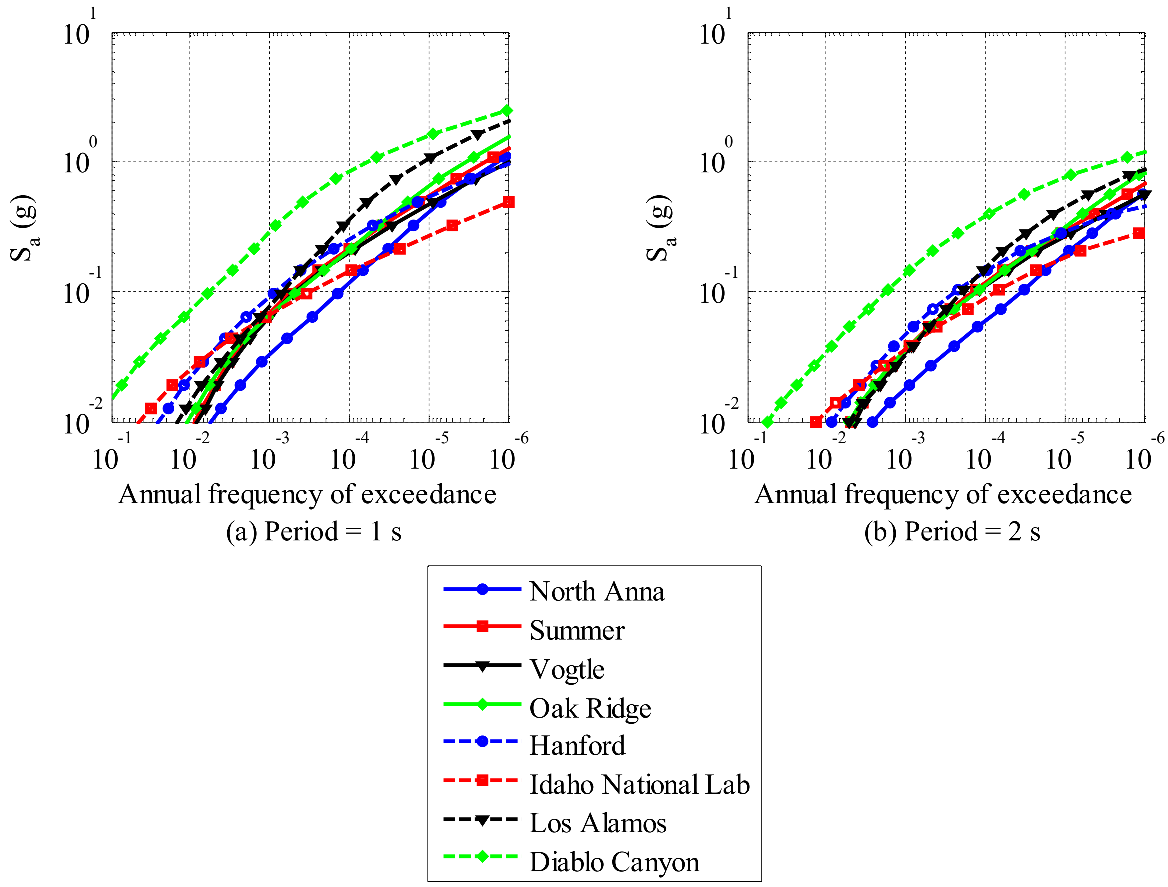

Figure 2. Seismic hazard curves for eight sites of nuclear facilities in the United States and 5% damping (adopted from Kumar et al. (2015)).

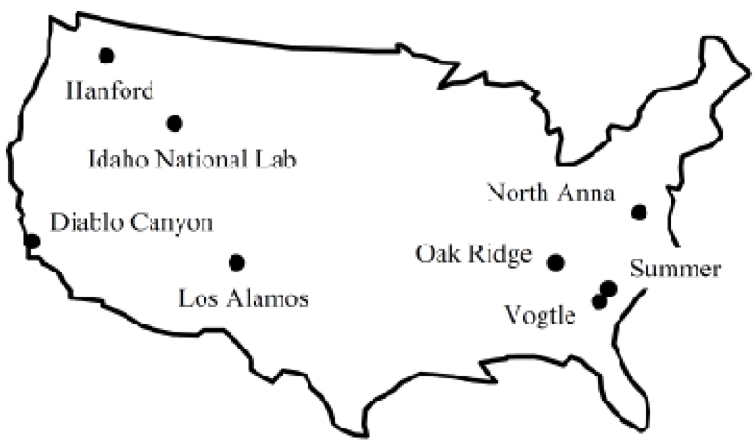

Figure 3. Location of eight nuclear facilities in the United States (adopted from Kumar et al. (2015)).

PERFORMANCE OBJECTIVES FOR ISOLATED NUCLEAR POWER PLANTS

Performance goals related to the isolation system outlined in Kammerer et al. (forthcoming) are: 1) the probability of the isolated superstructure striking the stop should be 1% (10%) or less for the GMRS+ (BDB GMRS) shaking, and 2) the probability of loss of axial load carrying capacity of the bearings should be 10% or less at a displacement equal to the clearance to the stop (CS). Assuming the stop is placed at the 90th percentile displacement for BDB GMRS shaking[2], these performance goals can be achieved by testing the bearings with 90+% confidence at the displacement equal to the CS and corresponding axial load. Table 1 presents the proposed performance and design expectations for isolated NPP structures.

Table 1: Performance objectives for seismically isolated nuclear power plant structures[1] (adapted from Kammerer et al. (forthcoming))

	Isolation system				
Ground motion levels	**Isolator unit and system design and performance criteria**	**Approach to demonstrating acceptable performance of an isolator unit**	**Superstructure design and performance**	**Umbilical line design and performance**	**Moat or stop design and performance**
GMRS+[2] Envelope of RG 1.208 GMRS and the minimum foundation input motion[3]	No long-term change in mechanical properties. Extremely high confidence of the isolation system surviving without damage when subjected to the mean displacement of the isolator system under the GMRS+ loading.	Perform production testing on each isolator for the mean system displacement under the GMRS+ loading and corresponding axial force.	Superstructure design and performance to conform to NUREG-0800 for GMRS+ loading.	Umbilical line design and performance to conform to NUREG-0800 for GMRS+ loading.	Moat gap sized such that there is less than 1% probability of the superstructure impacting the moat or stop for GMRS+ loading.
BDBE GMRS[4] Envelope of the UHRS at a MAFE of 1×10^{-5} and 167% of the GMRS+ per ISG 20	90% confidence of each isolator and the isolation system surviving without loss of gravity-load capacity at the mean displacement under BDBE GMRS loading.	Perform prototype testing on a sufficient number of isolators at the CS[5] displacement and the corresponding axial force to demonstrate acceptable performance with 90% confidence. Limited isolator unit damage is acceptable but load-carrying capacity must be maintained.	Less than a 10% probability of the superstructure contacting the moat or stop under BDBE GMRS loading.	Greater than 90% confidence that each type of safety-related umbilical line, together with its connections, shall remain functional for the CS displacement. Performance may be demonstrated by testing, analysis or a combination of both.[6]	Moat gap sized such that there is less than a 10% probability of the superstructure impacting the moat or stop for BDB GMRS loading. Stop designed to survive impact forces associated with isolation system displacement to 95th percentile BDBE isolation system displacement.[7] Limited damage to the moat or stop is acceptable but the moat/stop should perform its function.

1. Analysis and design of safety-related components and systems shall conform to NUREG-0800.
2. 10CFR50 Appendix S requires the use of an appropriate free-field spectrum (often the RG 1.60 spectral shape) with a peak ground acceleration of no less than 0.10g at the foundation level.
3. The analysis can be performed once using a composite spectrum or twice using the GMRS and the minimum spectrum separately.
4. The analysis can be performed once using a composite spectrum or twice using the 1×10^{-5} MAFE UHRS and the 167%GMRS+ separately.
5. CS=Clearance to the Stop
6. Seismic Category 2 SSCs whose failure could impact the functionality of umbilical lines shall also remain functional for the CS displacement.
7. Impact velocity calculated at the displacement equal to the CS assuming cyclic response of the isolation system for motions associated with the 95th percentile (or greater) BDB GMRS displacement.

ANNUAL FREQUENCY OF UNACCEPTABLE PERFORMANCE OF ISOLATION SYSTEM

Hazard Definition

For the calculations presented here, seismic hazard is defined in terms of the average of multiples, m, of the 1 s and 2 s UHRS ordinates[3, 4] at MAFE of 10^{-4}. The seismic hazard curves for the eight sites of Figure 3 are plotted in Figure 4.

[2] The 90th percentile displacement for BDB GMRS shaking is greater than the 99th percentile displacement for GMRS+ shaking (e.g., Kumar and Whittaker (2015), Kumar et al. (2015)).
[3] The ratio of the 1 s UHRS ordinates with an MAFE of 10^{-5} to 10^{-4} differs from that for the 2 s UHRS ordinates by 10% or less for the sites considered in this study (e.g., Kumar et al. (2015, 2017)).
[4] Spectral acceleration at a MAFE (e.g., 10^{-4}) is computed assuming a linear variation of spectral acceleration with MAFE in logarithmic space between adjacent data points of the seismic hazard curves of Figure 2.

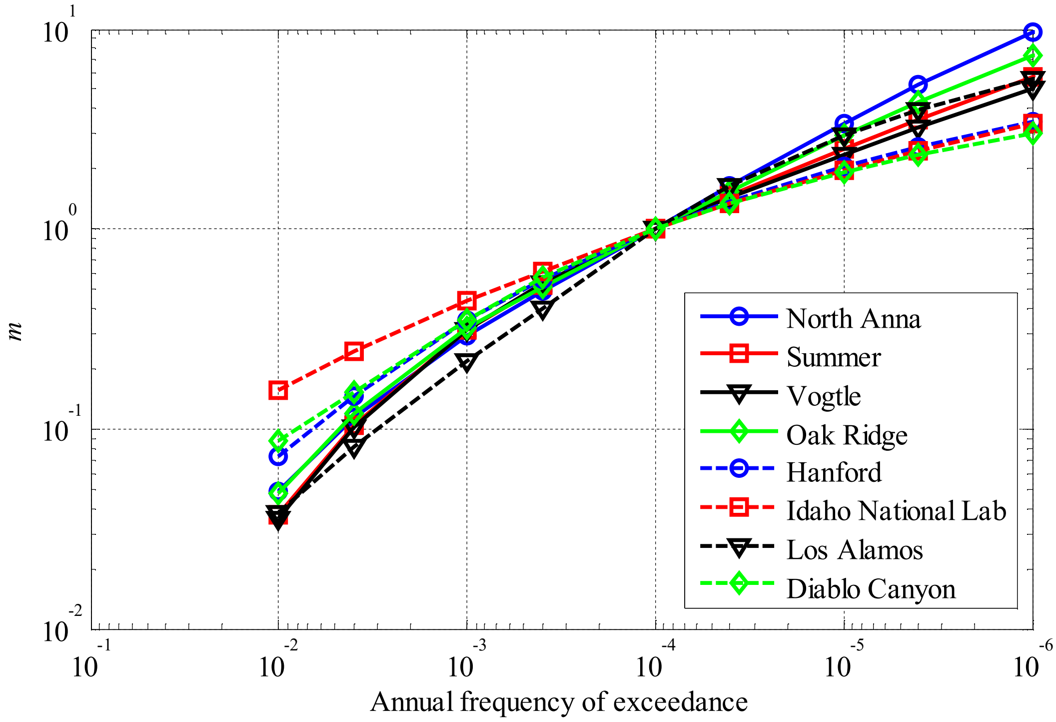

Figure 4. Annual frequency of exceedance of multiples, m, of UHRS with MAFE of 10^{-4} (adopted from Kumar et al. (2015)).

Fragility Curves

The failure of one isolator is assumed to trigger the failure of the isolation system: a very conservative assumption that considers demands and capacities of all the isolators in a system are fully correlated. The fragility curve for an isolator (and thus the isolation system) can be defined as follows

$$\theta - X_p \beta = \log(m) \tag{1}$$

where θ is the median and β is the logarithmic standard deviation , X_p corresponds to a probability of exceedance of p for a normally distributed data set, and m was defined previously. The value of β is set equal to 0.02 in this study because stringent quality control will be imposed on isolator production. (Results for other values of β are presented in Kumar et al. (2015, 2017).)

Per Table 1, isolators are *prototype* tested to confirm their axial load carrying capacity at a 90th percentile BDB GMRS displacement (the assumed location of the stop) and corresponding axial load with a 90+% confidence. The 90th percentile BDB GMRS displacement is approximately equal to the median 110% BDB GMRS displacement (see Kumar et al. (2015)): a transformation that enables the use of a consistent demand parameter for the risk calculations. Equation (1) can now be rewritten as

$$\theta - \alpha\beta = \log(f_{AR} \times m) \tag{2}$$

where α is 1.28, 1.64, and 2.33, respectively, for confidence levels on the isolator performance of 90% (1 failure in 10), 95% (1 failure in 20), and 99% (1 failure in 100), and f_{AR} is 1.1. Figure 5 presents the *median* fragility curves for the three confidence levels, $f_{AR} = 1.1$, and the eight sites of Figure 3. The isolators can be tested at displacements greater than the 90th percentile BDB GMRS (or median 110% BDB GMRS) displacement and corresponding axial load to reduce the risk (likelihood of failure). Figure 7 presents the fragility curve for 90% confidence of isolator performance tested at the median 125% BDB GMRS displacement $\left(f_{AR} = 1.25\right)$.

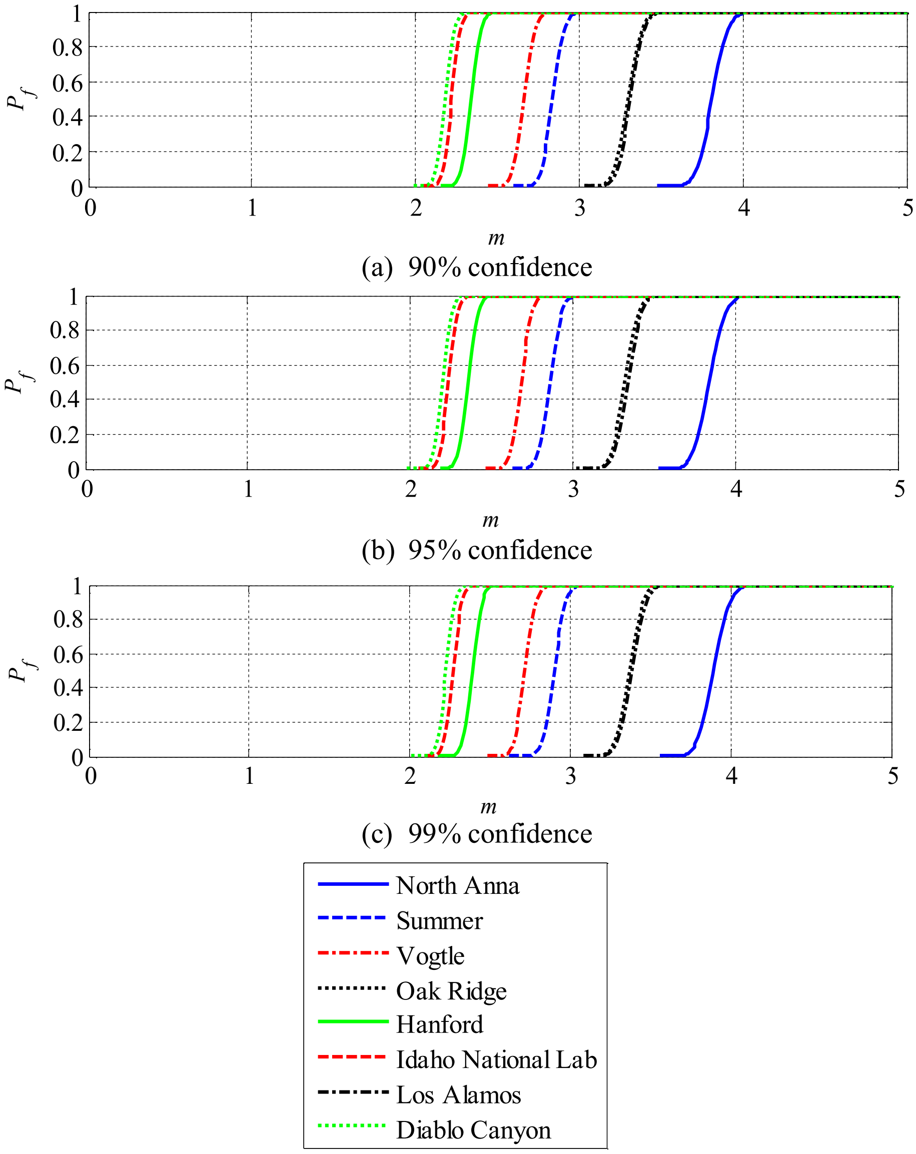

Figure 5. Probability of unacceptable performance, P_f, of individual isolator units for the three confidence levels on isolator performance at median displacement for 110% BDB GMRS shaking plotted against multiples, m, of UHRS shaking with MAFE of 10^{-4}, without a stop (adopted from Kumar et al. (2015))

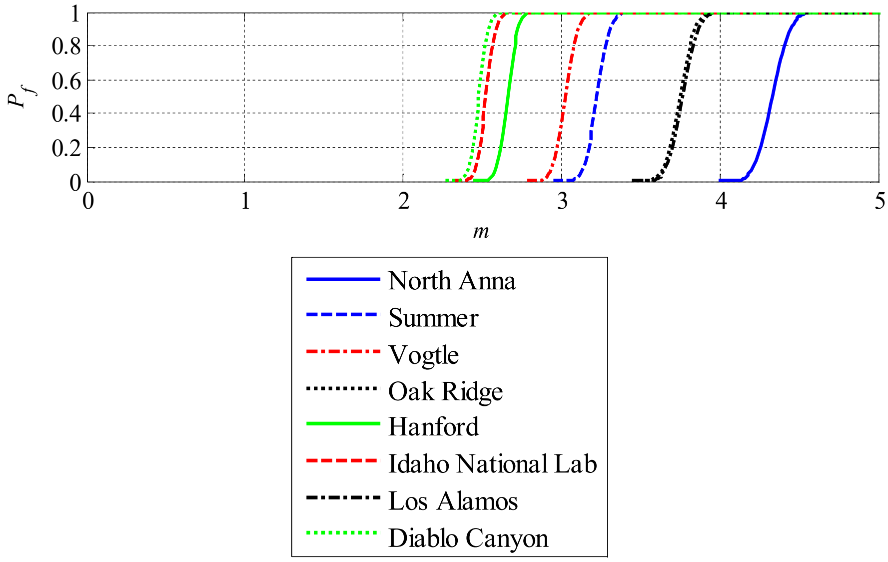

Figure 6. Probability of unacceptable performance, P_f, of individual isolator units for 90% confidence at median displacement for 125% BDB GMRS shaking plotted against multiples, m, of UHRS shaking with MAFE of 10^{-4}, without a stop (adopted from Kumar et al. (2015)).

The fragility curves of Figures 5 and 6 are for the isolation systems without a stop. These curves are truncated if a stop is present. Figure 7 presents the fragility curves for the cases considered in Figure 5, but with a stop installed at the 90th percentile BDB GMRS (or median 110% BDB GMRS) displacement.

Risk Calculations

The total annual frequency of unacceptable performance of the isolation system, $P_{F,\text{isolation}}$, is given by ASCE (2005):

$$P_{F,\text{isolation}} = -\int_0^{\infty} \frac{d}{dm} H_D \times \left(P_f \mid GM = m\right) dm \tag{3}$$

where H_D is the mean annual exceedance frequency of seismic hazard, $\left(P_f \mid GM = m\right)$ is the annual frequency of unacceptable performance for the m times UHRS shaking with an MAFE of 10^{-4}, and other parameters were defined previously.

Tables 2, 3 and 4 present the annual frequencies of unacceptable performance of the isolation system corresponding to the fragility curves of Figures 5, 6 and 7, respectively. The risk is reduced if the isolators are tested with either greater confidence to a given lateral displacement, or at a greater displacement and corresponding axial loads, for a specified level of confidence. For example, the annual frequency of unacceptable performance of the isolation system is reduced from 5.5×10^{-6} to 5.0×10^{-6} for the site of Diablo Canyon as the confidence of isolator performance is increased from 90% to 99% at the median 110% BDB GMRS displacements (see Table 2), and to 2.9×10^{-6} if the bearings are tested with 90% confidence at median 125% BDB GMRS displacement (see Tables 2 and 3). The annual frequency of unacceptable performance of the isolation system remains greater than 10^{-6} (the target goal of the authors of the NUREG for the seismic isolation system) for the confidence levels and displacements considered in this study, if a stop is not provided (Kumar et al. 2015, 2017).

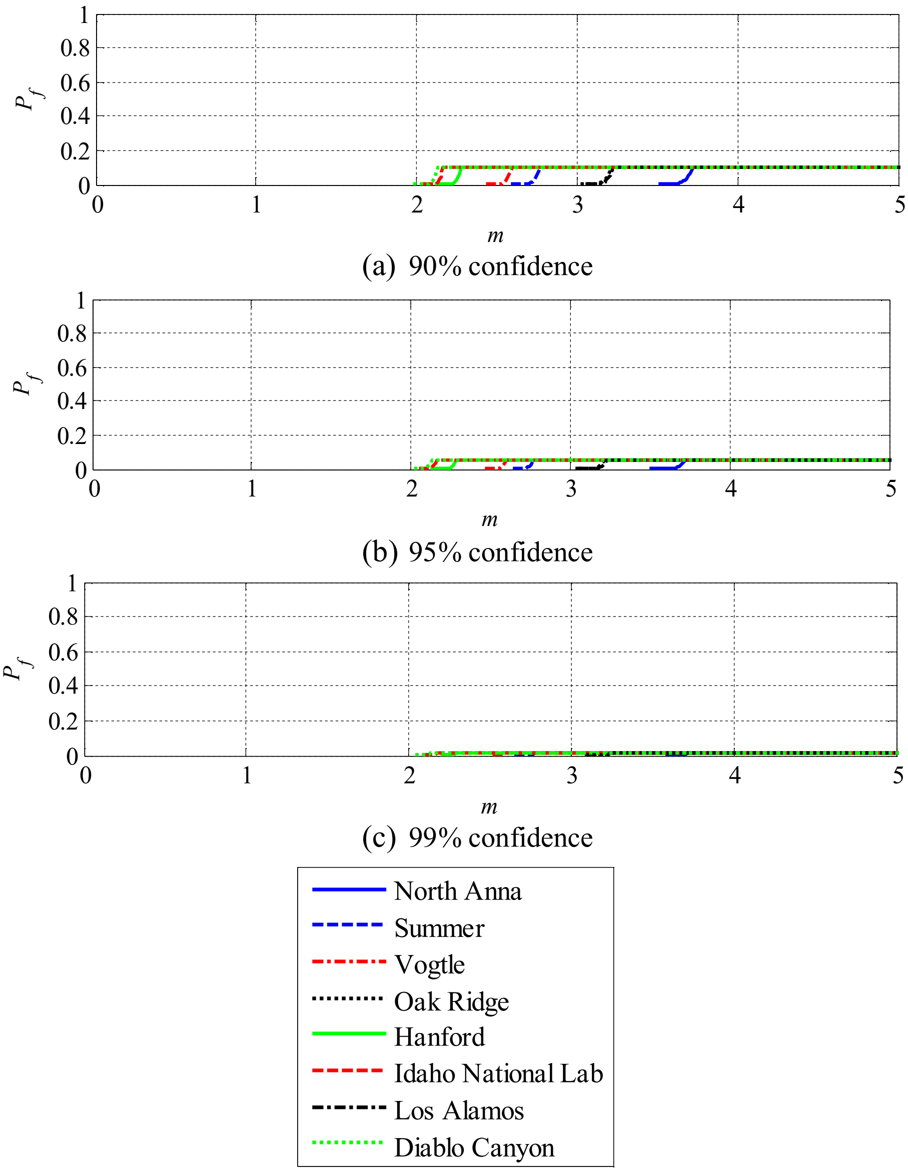

Figure 7. Probability of unacceptable performance, P_f, of individual isolator units for the three confidence levels on isolator performance at median displacement for 110% BDB GMRS shaking plotted against multiples, m, of UHRS shaking with MAFE of 10^{-4}, with a stop (adopted from Kumar et al. (2015)).

The seismic risk associated with the failure of the isolation system is substantially reduced if a stop is provided. Consider the Diablo Canyon site, 90% confidence, and median 110% BDB GMRS displacement. The risk reduces from 5.5×10^{-6} to 0.7×10^{-6} if a stop is provided (see Tables 2 and 4). In the presence of a stop, the risk is further reduced by a factor of 10 if the confidence on isolator performance is increased from 90% to 99% (see Table 4).

Table 2: Annual frequency of unacceptable performance ($\times 10^{-6}$) of individual isolator units tested at median displacement for 110% BDB GMRS shaking, without a stop.

Confidence	Site							
	North Anna	Summer	Vogtle	Oak Ridge	Hanford	Idaho	Los Alamos	Diablo Canyon
90%	7.8	7.2	7.0	7.5	6.2	6.2	6.9	5.5
95%	7.7	7.1	6.8	7.4	6.0	6.0	6.7	5.4
99%	7.5	6.8	6.6	7.2	5.6	5.7	6.4	5.0

Table 3: Annual frequency of unacceptable performance ($\times 10^{-6}$) of individual isolator units tested at median displacement for 125% BDB GMRS shaking, without a stop.

Site							
North Anna	Summer	Vogtle	Oak Ridge	Hanford	Idaho	Los Alamos	Diablo Canyon
6.0	5.1	4.7	5.6	3.6	3.6	4.6	2.9

Table 4: Annual frequency of unacceptable performance ($\times 10^{-6}$) of individual isolator units tested at median displacement for 110% BDB GMRS shaking, with a stop.

Confidence	Site							
	North Anna	Summer	Vogtle	Oak Ridge	Hanford	Idaho	Los Alamos	Diablo Canyon
90%	0.8	0.8	0.8	0.8	0.7	0.7	0.8	0.7
95%	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.3
99%	0.08	0.08	0.08	0.08	0.07	0.07	0.08	0.07

SUMMARY AND CONCLUSIONS

This paper summarizes a study on the seismic risk associated with the failure of an isolation system designed and tested in accordance with the forthcoming NUREG entitled “Technical considerations for seismic isolation of nuclear facilities”. Seismic hazard at sites of eight nuclear facilities across the United States are defined in terms of multiples of UHRS with an MAFE of 10^{-4}. Fragility curves for the isolation system are developed conservatively assuming that a single isolator represents the isolation system of an NPP, implying that the loss of axial load carrying capacity of an isolator constitutes the unacceptable performance of the isolation system. The risk is quantified in terms of mean annual frequency of unacceptable performance of the isolation system. Effects of testing the isolators to achieve a greater confidence and/or at a greater displacement, and installing a stop, are studied. A stop at the 90th percentile BDB GMRS (linked to the return period of 100,000 years) displacement is recommended for NPPs. Testing isolators to achieve a greater confidence or to horizontal displacements greater than the 90th percentile BDB displacement substantially reduces risk if a stop is provided.

The risk numbers presented in this paper assume that displacement capacities and demands are fully correlated. This assumption may be appropriate for an isolation system with a small number of bearings (say 4) but will be very conservative for a system with a) 100s of isolators experiencing similar lateral displacements but a wide range of axial forces (noting that prototype isolators are tested for maximum compressive and minimum tensile axial loads for all isolators in the system), and b) a thick basemat above the isolation system (see Figure 1), that will enable load redistribution in the event of the failure of one isolator.

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