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A COMPARATIVE STUDY OF METHODOLOGIES FOR SEISMIC PERFORMANCE EVALUATION WITH NONLINEAR FACILITY RESPONSE

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ABSTRACT

Nonlinear soil-structure system response of a nuclear facility can have a significant effect on its seismic performance utilized in a risk-informed decision-making process, even when designed to remain essentially elastic for a design response spectrum. However, the nonlinear system response effect is not captured in industry state-of-practice seismic performance evaluation methodologies. This paper presents and compares three candidate methodologies that were considered for use in seismic performance evaluation of a U.S Department of Energy facility experiencing significant nonlinear soil and structure responses at ground motion levels that contribute significantly to seismic risk computation. Selection and implementation parameters of the selected approach were based on a numerical experiment study using a simplified representation of the facility, which is summarized in this paper. Conclusions and recommendations for implementation in the full-scale study are presented. The use of a numerical experiment study illustrates that the relative effect of soil-structure system nonlinearities on seismic performance can be characterized prior to committing significant project resources, and thereby inform methodology selection.

INTRODUCTION

The U.S Department of Energy has adapted a performance-based approach for safety evaluation analysis of its non-reactor nuclear facilities (U.S. Department of Energy, 2016; U.S. Department of Energy, 2014). The approach establishes target performance goals that are a function of the offsite consequence of an accident initiated by natural phenomena hazards. Table 1 lists the target performance goals as a function of the seismic design category. The performance goal is defined as the acceptable mean annual frequency of a system, structure, or component (SSC) exceeding its specified limit state. It can be interpreted as an acceptable annual frequency of failure that corresponds to one of several seismic design categories (SDCs). The performance goals depend on the severity of adverse radiological and toxicological effects and range from those normally associated with SSCs important to safety (i.e., SDC-2); to those associated with legacy commercial nuclear power reactors (i.e., SDC-5).

The performance achieved is not typically computed for each SSC in new designs but is reasonably assured by following standard design practice that is consistent with these goals (American Society of Civil Engineers, 2019). Older existing facilities, however, may have been designed to less stringent criteria, or to a seismic hazard that is outdated. For these existing facilities, there may be a need to compute the expected seismic performance directly. ASCE 43-19 allows for alternate methods to meet the intent of the standard. One of those alternate methods includes computation of the performance directly, using "*appropriate site-specific hazard curves, demands, and capacities, with explicit consideration of uncertainty and variability.*"

Table 1: Performance Goals adapted U.S. Department of Energy for Non-reactor Nuclear Facilities

Seismic Design Category	Target Performance Goal
SDC-2	$P_F \leq 4 \times 10^{-4}$
SDC-3	$P_F \leq 1 \times 10^{-4}$
SDC-4	$P_F \leq 4 \times 10^{-5}$
SDC-5	$P_F \leq 1 \times 10^{-5}$

Seismic performance expressed as annual frequency of seismic-induced failure accounts for contribution from a range of ground motion amplitudes, including those beyond the design spectrum. For some ground motion amplitudes, soil-structure system nonlinearities will occur. The ground motion range where such nonlinearities occur can be significant to the expected seismic performance of a given facility. Therefore, methodologies for seismic performance evaluation which account for these nonlinearities are desirable.

This paper presents three methodologies for use in computing the seismic performance of an SSC including the effects of the facility's nonlinear soil-structure system response in estimation of seismic fragilities and subsequent impact on performance and reports on a numerical experiment performed using two of these approaches. Though the principles underlying these methodologies are technically established, they have not typically been used on nuclear facilities with a few recent exceptions.

METHODOLOGIES FOR COMPUTATION OF SEISMIC PERFORMANCE

We considered three methodologies, herein referenced as Approaches 2a, 2b, and 3. For reference, the current state of practice is introduced and reviewed as Approach 1:

1. **Approach 1;** Approximate second moment procedure for seismic fragilities. A single review-level earthquake (RLE) ground motion spectrum shape is used to generate probability distributions of demands. The demand is considered to scale linearly with the ground motion amplitude in vicinity of the RLE.
2. **Approach 2a;** Intensity measure (IM)-based multiple stripe approach (MSA); wherein time histories are conditioned to produce a broad spectrum (typically uniform hazard spectra (UHS)). Multiple ground motion "stripes" (annual frequency of exceedance bins) are used to produce distributions of demand at each stripe.
3. **Approach 2b;** IM-based multiple stripe approach; wherein time histories are conditioned to produce Conditional Spectra (CS), which consists of the Conditional Mean Spectrum (CMS) and

the variability about it at each hazard exceedance level. Approach 2b differs from approach 2a in that the time history input motions are conditioned to spectral shapes that exhibit variability around a smooth spectrum.

4. **Approach 3;** Engineering Demand Parameter (EDP)-based multiple stripe approach using Conditional Scenario Spectra (CSS).

Each of these approaches is discussed in more detail in the following subsections. Potential sources of conservatism or lack of conservatism embedded in each of the approaches are identified.

Approximate Second Moment Approach (Approach 1)

The Approximate Second Moment Approach is typically used in seismic probabilistic risk assessments (SPRAs). It is a relatively quick and non-computationally expensive process which produces a single mean point estimate of performance (i.e., risk) through convolution of the mean seismic hazard with the mean seismic fragility for the governing (or representative) limit state, when seismic hazard and seismic fragility are functions of the same ground motion variable. This is especially convenient when the seismic fragility is expressed in terms of a ground motion intensity measure (IM) such as peak ground acceleration (PGA) or spectral acceleration. This approach was introduced in the nuclear industry in the 1980s as a result of industry research into SPRA (Kennedy and Ravindra, 1984; EPRI, 1994).

The seismic fragility is typically expressed in terms of the best estimate of the median ground acceleration capacity, $\breve{A}$ and two random variables. The ground acceleration capacity, A, is given by:

$$A = \breve{A}\varepsilon_U\varepsilon_R \tag{1}$$

in which ε_U and ε_R are lognormal random variables with unit medians that represent inherent randomness and epistemic uncertainty, respectively. They have logarithmic standard deviations β_U and β_R, respectively.

The mean annual frequency of unacceptable performance, P_F, is determined by convolving the mean fragility (whose $\beta^2 = \beta_U^2 + \beta_R^2$) with the mean hazard (either Equations 2 or 3):

$$P_F = -\int_0^\infty \left(\frac{dH(a)}{da}\right) P_{F|a}(a)da \tag{2}$$

$$P_F = \int_0^\infty H(a) \left(\frac{dP_{F|a}(a)}{da}\right) da \tag{3}$$

where H(a) is the mean annual frequency of exceedance of ground motion level "a", as defined in the seismic hazard curve, and $P_{F|a}(a)$ is the cumulative conditional density function that defines the probability of unacceptable performance given the ground motion level "a". H(a) and $P_{F|a}(a)$ represent the mean seismic hazard and fragility curves, respectively.

The primary drawback of this approach is that the accuracy of the risk computation is dependent on the choice of RLE from which fragility parameters are computed using the ratio of capacity to the demand, because linear response scaling is assumed to occur. The accuracy is maximized when the ground motions around the RLE level represent the primary contribution to seismic risk as predicted by the performance calculation. However, identifying this RLE prior to the performance calculation is performed is difficult. Use of design response spectra as the RLE, although convenient, can introduce meaningful inaccuracy. For example, the margins used in seismic design are such that the performance of components may sometimes be governed by ground motions significantly higher than the design response spectra, and the Approach 1 demand determined with the RLE at the design level may ignore potential nonlinear response of the soil or structure above that RLE. This may be conservative, such as for robust structures placed on soil where soil softening is predicted to occur before structure damage.

Approaches 2a and 2b – IM-Based Multiple-Stripe Approach

In order to explicitly capture the influence of nonlinear soil and structure response, multiple hazard levels can be considered. Each approach begins with defining ground motions consistent with the probabilistic seismic hazard assessment (PSHA). For Approach 2, the computation of the mean probability of failure given ground motion level “a,” $P_{F|a}(a)$, is performed explicitly at each discrete hazard level (or IM level). The conditional mean probability of failure as a function of IM is generated by interpolation or fitting to these explicitly calculated values. The mean annual frequency of failure is then calculated using Equation 2. Approach 2 is based on multiple-stripe approaches suggested by previous researchers (Jalayer and Cornell, 2008; Baker, 2015; Bolisetti et al., 2017) and adopted in the “time-based assessment” approach in FEMA P-58 (FEMA, 2018). The use of multiple discrete hazard levels has precedence with the probabilistic dynamic response calculation aspects of the seismic safety assessment approach developed in the Seismic Safety Margins Research Program (SSMRP) (Smith et al., 1981).

Approach 2 offers more flexibility than Approach 1 to accommodate different time history suites at each hazard level. Baker (2015) and Bolisetti et al. (2017) studies are examples of multiple-stripes analyses wherein structural analyses are performed at discrete sets of IM levels, with different ground motions used at each level. This allows the time-history suite development to account for the changes in ground motion target properties at increasing IM levels.

We considered two input time history suite development methods for Approach 2. Approach 2a conditioned and scaled seed time history record sets to produce spectra which tightly matched the UHS for the given hazard level. Approach 2b conditioned and scaled seed time history record sets to produce CS that reproduce the CMS at a particular conditioning period and the conditional variability in spectral accelerations at other frequencies (Arteta and Abrahamson, 2019).

The main advantage of the multiple stripes approaches is that the fragility parameters are corrected for nonlinear response of elements in the demand by performing nonlinear simulations at “*n”* distinct levels of ground motion. This raises the question of how many stripes are needed for accuracy. A disadvantage of the multiple stripes approach is that it can be computationally exhaustive. Some precedence exists for the number of stripes to be selected between four and eight, with 30 to 60 simulations per stripe.

Approach 3 – EDP-Based Multiple Stripe Approach Using Conditional Scenario Spectra

While seismic ground motion input at various hazard levels has been traditionally defined by UHS or spectra derived from the UHS, alternate methods of ground motion record selection for computation of system performance have been advanced through the PEGASOS Refinement Project (Renault et al, 2015) and elsewhere (Arteta and Abrahamson, 2019). The PEGASOS Refinement Project used scenario spectra for individual earthquakes for use in seismic risk assessment. Magnitude and distance for the scenarios were based on the magnitude-distance deaggregation from PSHA. The scenario spectra were developed using conditional spectra and with rates of occurrence assigned to each scenario such that their calculated hazard matches the target horizontal and vertical hazard curves for a range of hazard levels and frequencies of interest. This approach was extended and termed the CSS in Arteta and

Abrahamson (2019). The implementation in Arteta and Abrahamson (2019) focused on EDP variability due to ground motion randomness. It can be extended to include EDP variability due to other sources.

The CSS approach differs fundamentally from Approach 1 and Approach 2 in that Approach 3 describes the fragility in terms of EDP conditional distributions given each scenario and corresponding recurrence rate instead of EDP conditional distributions given the IM. Approaches 1 and 2 assume that the fragility may be expressed in terms of a single ground motion parameter, which is an incomprehensive predictor for nonlinear response affecting various component limit states. Variant implementations of the CSS approach have been applied to nuclear power plants in Switzerland (Renault and Abrahamson, 2015) and in Talaat et al. (2015) to develop improved risk estimates.

The main advantage of Approach 3 is that it uses recorded earthquake motions without conditioning and represents the seismic hazard space on a continuum rather than discrete strips. It is believed that the time history suites developed using Approach 3 represent the most realistic input to be used in probabilistic simulations given current technology. Its main disadvantage is that it typically takes many hundreds of scenario spectra to reproduce the hazard space, which may be computationally prohibitive to compute EDP distributions via nonlinear soil-structure-interaction (SSI) simulations with sufficient fidelity to benefit from the enhanced rigor of those inputs .

NUMERICAL EXPERIMENT STUDY

A numerical experiment was conducted as part of a seismic performance evaluation project for an existing facility. Its objective was to simulate the horizontal response and expected performance of a low-rise shear wall structure at LANL in order to explore various approaches for computing seismic risk given nonlinear soil-structure system response. The numerical experiment used a reduced-order representation of the structure and underlying soil with fully nonlinear material properties. Inputs and results of the experiment are summarized herein. A detailed presentation of the experiment is documented in SGH (2021).

The prospect of implementing Approaches 1, 2a, 2b, and 3 were discussed by the various project stakeholders at a number of project technical workshops. It was agreed that incorporation of nonlinear effects is important because a meaningful contribution to performance was anticipated to occur at large ground motions for which nonlinear effects are expected, necessitating either Approaches 2 or 3. Approach 2 was selected for use in the project, primarily because of the following reasons:

- Approach 3 may require significantly more nonlinear simulations than Approach 2 in order to consistently represent SSI model uncertainty.
- Approach 2 is currently more familiar to industry practitioners and has well-established implementation precedents. This facilitates developing streamlined guidance for implementation and criteria for checking, verification, and peer review.
- Approach 2 defines the fragility in terms of the Intensity Measure, which is more easily understandable by involved stakeholders and relatively easier to reuse, e.g., to incorporate minor updates in the PSHA. LANL has a PSHA update planned in the near future.

While the project stakeholders concluded that Approach 2 would presently be more effective to implement and communicate to review bodies for this project, this selection does not imply that Approach 2 is a better or universally preferred method for use in seismic performance assessment than Approach 3.

Objectives of the Experiment

The numerical experiment assessed the relative cost-effectiveness of Approaches 2a and 2b using a systematic investigation process. The experimental results could also be compared to previous risk results obtained using Approach 1. The experiment focused on comparing the two approaches with respect to:

1. The difference in estimated mean performance,
2. The difference in the level of confidence in the estimated performance, and
3. The difference in the level of effort required to adequately compute the mean performance

A number of parameters were investigated to compare and contrast the efficacy of each investigated approach. Those parameters are summarized in Table 2.

Table 2: Considerations investigated to assess effectiveness of alternate performance approaches

LHS Design Considerations	**Precision and Robustness Considerations**
• Number of required SSI model realizations for stable results • Number of required time history input motions • Overall number of required simulations (SSI-model to input motion pairings)	• Sensitivity to extreme inputs and outlier simulation results • Sensitivity to fragility function smoothing • Influence of SSI model validity at high ground motions • Influence of hazard level range of SSI simulations • Sensitivity to interpolation within hazard range of SSI simulations • Sensitivity to earthquake hazard intensity measure

Numerical Experiment Overview

The effectiveness of the two candidate performance assessment approaches was assessed using a systemic sensitivity study investigation process. Figure 2 shows an example flowchart of the process used to investigate the precision and robustness considerations. Elements of the experiment consisted of:

- Mean seismic hazard curves defined for motion at a defined rock outcrop.
- Ground motion acceleration time history input record sets developed consistent with this mean hazard using Approaches 2a and 2b.
- An idealized nonlinear soil structure interaction model.
- A randomized suite of the numerical experiment SSI model accounting for the range of properties.
- Definitions of EDPs as wall drift ratios and corresponding failure criteria for a representative limit state related to the safety function of the real shear wall structure.

The output of the experiment were distributions of EDP and soil strains at several hazard stripes, IM-based fragility curves, and mean annual rates of reaching the identified limit state. The simulations in the experiment were systematically controlled to vary selected input variables that represent the considerations selected and examine the influence on the outcome for both approaches. The conclusions from the outcome of these simulations were compared to develop answers for the questions identified above, select a favoured approach, and develop implementation recommendations for it.

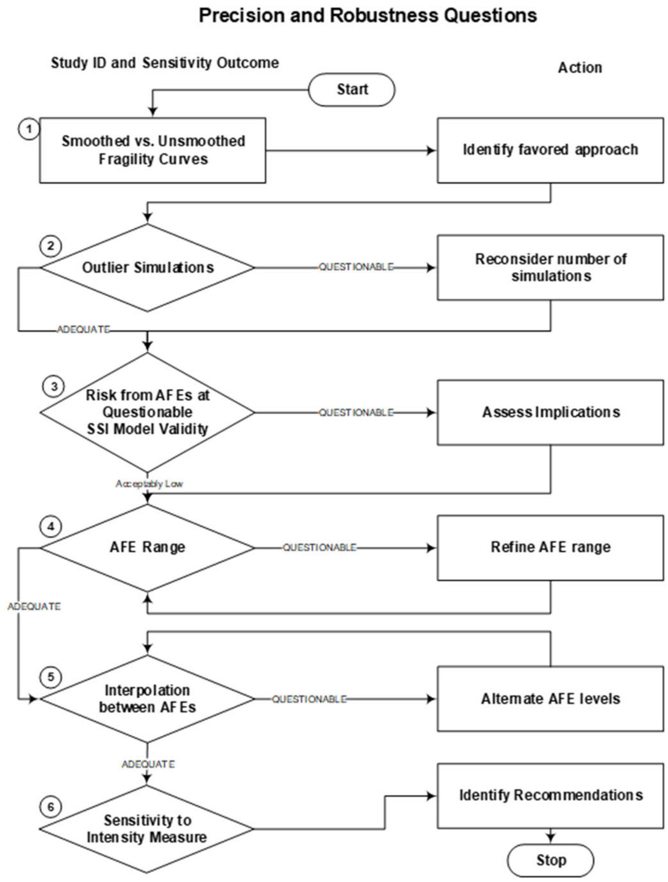

Figure 2 Process for investigating requirements of precision and robustness

NUMERICAL EXPERIMENT RESULTS

Each of the considerations listed in Table 2 were investigated using a series of sensitivity studies. The objective of the studies was to determine the appropriate sizes of the LHS design dimensions required to produce statistically stable EDP probability distributions from the analysis and stable corresponding risk estimates from the candidate performance assessment approaches. A typical result is shown in Figure 3.

Figure 3 shows summary parameters of the wall drift ratio probability distributions generated using 30, 60, and 120 SSI models using a single time history input developed using Approach 2a at the 4×10^{-4} annual frequency of exceedance hazard level. The summary consists of comparing the median, 84% non-exceedance probability (NEP), and maximum drift ratios from each set. Review of the results indicates that the median, 84% NEP, and maxima values are nearly identical for 60 and 120 models. The summary parameters generated using only thirty models are not significantly different from the other two cases. At this input motion level, the SSI model response exhibits only limited nonlinearity. At higher input motions, the difference between the latter case and the former two became more noticeable. SGH (2021) presents a full set of comparisons and observations for both approaches.

The experiment also investigated the sensitivity of the calculated annual performance. This comparison was made for both Approaches 2a and 2b and investigated a number of parameters. A typical comparison is shown in Figure 4. This figure shows the mean performance estimates using various number of SSI simulations and different types of pairings of the SSI model and input motion records. The outcomes of the experiment are summarized in the conclusions section.

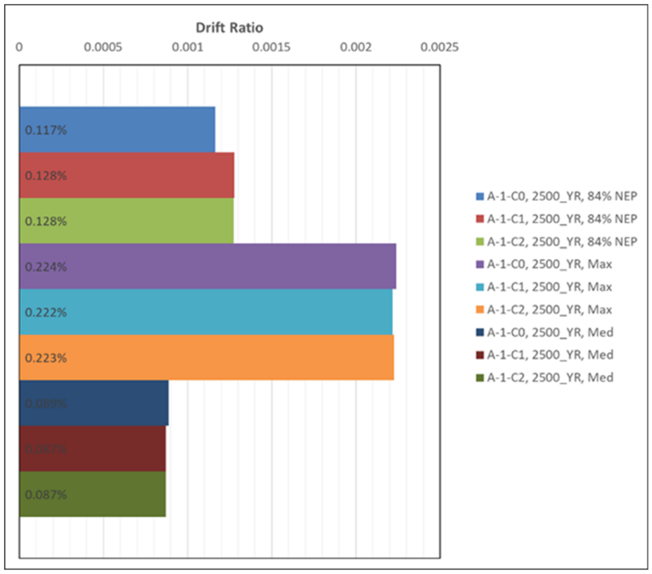

Figure 3 Distributions of Wall Drift Ratios for Alternate Numbers of SSI Models (C0, C1, C2 = 30, 60, 120), given 4E-4 mean annual frequency of exceedance UHS-matched input motions (Approach 2a)

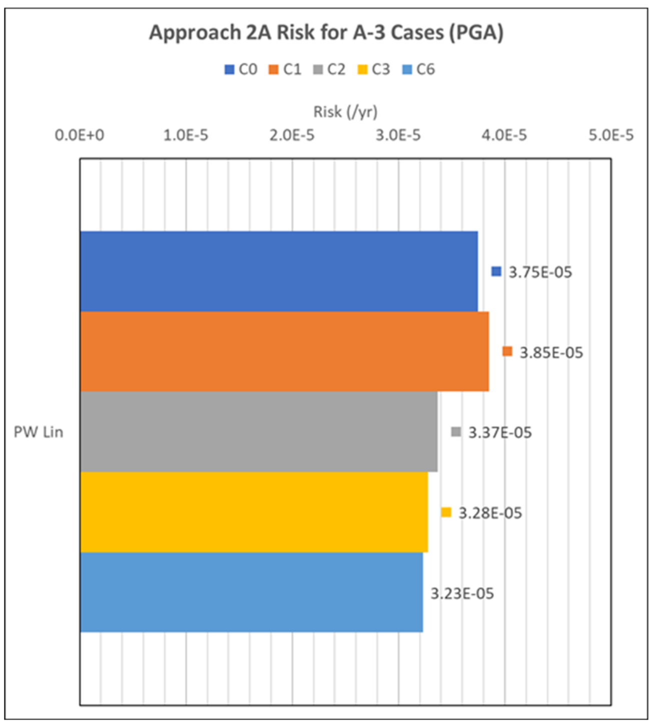

Figure 4 Distributions of Wall Drift Ratios for Alternate Numbers of SSI Simulations (C0, C1, C2, C3, C6 = 60, 60, 120, 240, 3,600, given 4E-4 mean annual frequency of exceedance UHS-matched input motions (Approach 2a) and piecewise linear fragility interpolation

CONCLUSION

The salient conclusions from the numerical experiment study are summarized in Table 3. More details are found in SGH (2021). These conclusions and recommendations are being adopted for the ongoing seismic performance assessment project of the facility using detailed finite element models. The numerical experiment provided a cost-effective tool to methodically explore several aspects and decision sequences for the performance assessment project and make facility-specific recommendations, including selecting the performance evaluation approach and its implementation details, the LHS design, the parameter randomization process for the probabilistic simulations (not presented here), and other decisions that would have been prohibitive to explore using the detailed facility model. The methodologies demonstrate that seismic performance evaluations of nuclear facilities can account for nonlinear soil-structure system behaviour, which can have significant influence though predicted to remain elastic at the design earthquake.

Table 3: Summary of Recommendations for Implementation

Attribute	Recommendations	Basis for Recommendation
Approach	Use Approach 2a.	Approach 1 ignores non-linear response effects. Mean performance computed between Approaches 2a and 2b were not significantly different. Approach 2a demonstrated more stable results with less computational cost.
Seismic Hazard Characterization	Use mean hazard curves at rock outcrop. The lowest hazard levels should target a probability of failure of about 2%. The highest level should correspond to the limit of the SSI model validity or to about 90% of the cumulative risk.	Sensitivity studies that examined the change in computed risk as a function of ground motion inputs and the number of stripes used.
Input ground motion simulations	Use at least 30, three-component records sets at each stripe. Develop new suites of records at each stripe as opposed to scaling. At low probabilities of failure, double the size of the records sets (or reuse the existing suite rotated by 90 deg).	Sensitivity studies demonstrated that EDP distributions are relatively insensitive to increasing the number of records beyond 30.
SSI model randomization	Randomly pair SSI models with each ground motion set. A larger number of ground motion pairings may be needed for failure modes that dominate performance.	Sensitivity studies demonstrated that the performance estimate for Approach 2a is largely stable for a single random pairing, unlike Approach 2b (at least four pairings were required)
Fragility curve smoothing	Estimate mean probability of failure at each stripe. Smooth resulting fragility curve using regression.	The smoothed fragility curves mitigate sensitivity of performance estimate to the number of simulations. Sensitivity studies demonstrated only a slight conservative bias due to smoothing.
Risk computation	Convolve the smoothed fragility with the discretized hazard curve. Use hazard curves for multiple intensity measures to confirm low sensitivity to UHS shape changes between stripes.	Approach 2a did not exhibit sensitivity to the hazard IM while Approach 2b was sensitive when record selection and scaling were performed following the state of practice.

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