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ASSESSMENT AND USE OF PROBABILISTIC FLOOR RESPONSE SPECTRA FOR SEISMIC EVALUATION OF SYSTEMS AND COMPONENTS IN NUCLEAR POWER PLANTS

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ABSTRACT

This paper examines two (2) established methodologies for developing Floor Response Spectra (FRS) for use in the seismic qualification of safety equipment in nuclear power plants (NPPs). One is embodied (for example) in the Nuclear Safety Standards Commission's KTA 2201.3 (2015), and the second is described in the American Society of Civil Engineers' ASCE 4-16 (2017). Both methods use seismic soil-structure interaction (SSI) analysis of the plant structures. Of the two methods, KTA 2201.3 (2015) is based on deterministic seismic SSI analysis whilst ASCE 4-16 (2017) recommends the more recently introduced Probabilistic SSI (PSSI) approach.

The question of consistency between deterministic and probabilistic approaches was already raised in different licensing reviews and has been addressed in numerous technical publications. In the Swiss regulatory environment, the goal of consistency between the two approaches is even more challenging because the Nuclear Energy Ordinance (732.11 (2004)) and the Radiological Protection Ordinance (SR 814.501 (2017)) along with related guidelines issued by the Swiss Federal Council require that both approaches be used for safety assessment and for the characterization of postulated incidents and accidents in a somewhat consistent manner. Internationally, the IAEA also recommends that such complementary assessments be conducted in a more structured framework (IAEA INSAG-25 (2011)).

This paper examines the respective attributes and technical merits of deterministic and probabilistic methods, predicated on the objective that both the seismic demand and the structural capacity evaluation have sufficient conservatism to meet the performance goals. It is concluded that the PSSI analysis provides a sufficiently conservative basis whilst at the same time being more representative in the context of quantitative performance goals. This supports the use of the 84th percentile PSSI spectra for deterministic proof of safety analysis, and the realistic 50th percentile PSSI spectra for fragility analysis.

This paper also presents a structured approach to calculate and store location specific FRS in databases tables, for scripted retrieval and use in the subsequent deterministic proof of safety analysis and fragility analysis.

INTRODUCTION

Prior to about the year 2000, largely because of limitations in computing power, the seismic response of nuclear facilities was almost exclusively obtained using deterministic seismic SSI analyses of simplified analytical models where the building structure was represented by lumped stiffness and mass. Further, the models were characterized by the best estimate (BE) structure stiffness and damping parameters, and three (3) subsurface soil conditions, namely the best estimate (BE), lower bound (LB) and upper bound (UB) accounting for uncertainties in soil stiffness and damping. Thus, the variabilities in the structure stiffness and damping and in the soil stiffness and damping were considered in a limited manner, and the resulting floor response spectra (FRS) were peak broadened, so that the uncertainties in predicting the peak frequencies were considered in the seismic qualification of equipment.

ASCE 4-86 (1986) refined the peak-broadening methodology somewhat in recognition that the "…same uncertainties which lead to broadening of in-structure response spectrum peaks also lead to reduction in the peak spectral amplitudes with a given probability of exceedance…". This concept, substantiated by several PSSI analyses was continued in ASCE 4-98 (1998). In lieu of performing a probabilistic evaluation, a 15% reduction in peak amplitude of deterministic spectra was deemed reasonable and conservative. This mitigates some of the unintentional and uncontrolled conservatisms introduced by the peak broadening alone. The intent of this provision in ASCE 4-86 (ASCE 4-86 (1986)) and ASCE 4-98 (ASCE 4-98 (1998)) was to introduce a 90% non-exceedance probability for the seismic demand on plant structures, systems and components (SSCs) over a broad range of frequencies.

Similarly, KTA 2201.3 (2015), also recommends limited peak reduction. "…Capping spectrum tips from widths that are less than 10 % of the respective centre frequency…". Additionally, the KTA 2201.3 (2015) recommends using three (3) time-history sets to obtain average FRS. The resulting averaged FRS for three (3) soil conditions are broadened and enveloped. In this respect, the KTA 2201.3 (2015) considers the variabilities associated with the ground motion only in a limited manner. Consistent with the methodology, the requirements in the KTA 2201.3 (2015) are also interpreted to achieve a goal of 90% non-exceedance probability for seismic demand on SSCs.

Subsequent to ASCE 4-98 (1998), the ASCE Standards Committee for Dynamic Analysis of Nuclear Structures (DANS) updated the Standard to implement recent developments in seismic analysis of NPP facilities (e.g., more widespread use of finite element models to represent the structure stiffness and damping). The updated standard, ASCE 4-16 (ASCE 4-16 (2017)) is intended to work with ASCE Standard ASCE 43-05 (2005) which has been used as a reference document in several recent combined license applications (COLAs) for new reactors. The revised Standard ASCE 4-16 targets about an 80% non-exceedance probability response, given the mean uniform hazard ground motions at the plant site. The basis for this is that the 80% non-exceedance demand when used with conservatively biased code capacities results in the desired quantitative performance goal of less than 1% probability of failure at the design basis earthquake. Concurrently, the failure is defined in terms of performance requirements associated with functionality, recoverability, structural integrity or incipient collapse which determines the code allowable capacities.

In contrast to previous standards, the more recent approaches embedded in ASCE 4-16 and in ENSI-AN-8567 (2014) are targeted to result in component designs having the desired High Confidence of a Low Probability of Failure (HCLPF) levels. HCLPF values are quantitatively characterized by a 5% probability of failure with 95% confidence, or alternatively 1% probability of failure on the composite fragility curve) (EPRI-TR 103959 (1994)). The knowledge of HCLPFs allows for the integration of the design with fragility approaches to provide risk-informed insights. In addition, the more recent approach recognizes the necessity for better integration between Deterministic Safety Assessment (DSA) and Probabilistic Safety Assessment (PSA) as a key issue in today's safety assessments. As recommended by

IAEA in IAEA INSAG-25 (2011) for example, there is an important need for complementary assessments in a structured framework considering both DSA and PSA approaches on equal footing.

More notably, the current standards (e.g., ASCE 4-16 (2017)) represents that PSSI analysis is the preferred approach to quantitatively determine the FRS with an 80% non-exceedance probability. In Section 5.1.7 ASCE 4-16 states that "…The preferred treatment of uncertainties in the SSI analysis is the use of probabilistic techniques (Section 5.5). In such an approach, the resulting design quantities would be established at a non-exceedance probability of approximately 80% to meet the goal of this standard…". This preference reflects the improvements in the response prediction capabilities and also the significant improvements in computing power, which allows for many more analyses to develop more stable statistics.

DETERMINISTIC VS PROBABALISTIC SEISMIC ANALYSIS

The current practice in the U.S. as described in ASCE 4-16 (ASCE 4-16 (2017)) requires that deterministic SSI analysis use at least three (3) sets of site-specific soil profiles with appropriate coefficient of variation (COV) and that the analysis should be performed using three (3) sets of acceleration time histories for each profile.

The KTA 2201.3 (KTA 2201.3 (2015)) Standard is somewhat more extensive relative to ASCE 4-98 (ASCE 4-98 (1998)). However, it still accounts for the overall uncertainties in a limited and intractable manner. For example, the FRS from the three (3) input time history sets are averaged and subsequently peak-clipped, broadened and enveloped. Although, this procedure is expected to result in non-exceedance probabilities of the response in excess of 80%, the process is approximate and does not provide insights into the conservatism or unconservatism in the seismic design of systems and components.

On the other hand, the preferred treatment in ASCE 4-16 (ASCE 4-16 (2017)) accounts for uncertainties in the SSI analysis more rationally by means of the probabilistic method. The resulting information can establish design quantities at the desired non-exceedance probability level in a more traceable manner. The resulting probabilistically combined FRS calculated at about an 80% non-exceedance probability level are recommended as inputs to the seismic analysis and/or qualification of subsystems with the intent of meeting the Standard's goal of less than 1% probability of unacceptable performance (i.e., failure) for the design basis earthquake ground motion.

The PSSI for a NPP structures are performed using the widely accepted Latin hypercube simulations (LHS) method. Based on their cumulative probability distribution functions, each variable value (structure stiffness, structure damping, soil stiffness and soil damping) corresponding to an incremental probability is binned into 30 bins. Each variable value is expressed in terms of multipliers of the respective parameters of the base case model. The SSI models for the 30 LHS simulations are built using randomly selected multipliers from each bin and randomly selected input time history set (out of 30-time history sets). The full set of response simulations is assembled by repeating this sampling process, without replacement, a total of 30 times until the values in all probability bins are exhausted.

The resulting 84th percentile responses are used to perform the deterministic proof of safety analyses of selected SSCs, while the 50th percentile responses are used in the fragility analyses of selected SSCs. The resulting HCLPF values from the fragility analysis typically compare very well with the HCLPFs resulting from the deterministic proof of safety evaluations with the possible exception of components whose resonant frequency is close to the dominant SSI frequency. This provides yet another reason for using about 80th percentile FRS (specifically 84th in this case), rather than more conservative demand values such as 90th or 95th percentile FRS, to satisfy the performance goals set in the modern Standards and ensuring a better integration between DSA and PSA.

The following section compares the PSSI floor spectra with the deterministic floor spectra using the KTA 2201.3 (KTA 2201.3 (2015)). Based on this comparison, it proposes possible refinements in the methods to treat uncertainties in the deterministic spectra.

COMPARISON OF BUILDING DETERMINISTIC AND PROBABILISTIC FRS

Figure 1 through Figure 3 compare the 84th percentile PSSI spectra with the envelop of the deterministic FRS associated with BE, LB and UB soil conditions for top of RPV pedestal, steam tunnel floor and internal drywell wall, respectively. These FRS are obtained from the SSI analysis of the Reactor Building. The comparison is done for all three (3) directions, namely horizontal X and Y directions and vertical Z direction. The deterministic spectra are peak clipped (by 10%) and enveloped in accordance with the KTA 2201.3 (KTA 2201.3 (2015)). However, to provide more meaningful insights the peaks are not broadened.

The comparisons of FRS in Figure 1 through Figure 3 illustrate that the requirements for the deterministic approach described in the KTA 2201.3 (KTA 2201.3 (2015)) result in seismic responses that are reasonably close to the probabilistically developed 84th non-exceedance probability spectra if peak broadening is not applied, and thus are suitable for performing design basis seismic evaluations of new installations.

In order to assess the differences (i.e., consistency) between the PSSI and DSSI approaches, a measure for the relative deviation is employed because neither one is currently taken to be the “correct” reference value for design. Defining a relative deviation is not as straightforward as defining a relative change relative to an accepted baseline. Even though the PSSI analysis is likely to deliver superior response results, neither the PSSI results (designated by x) nor the response quantities based on KTA 2201.3 (designated by y) are taken here to represent the baseline a priori. Rather, a simplistic relative error formulas like $d_{Rel} = x / y - 1$ is replaced by more appropriate relative deviation formulation to measure the intrinsic relative deviation (Wolfram MathWorld (2020)):

$$d_{Rel} = \frac{x}{|x+y|/2} - 1 \tag{1}$$

Where d_{Rel} is the relative error for x and y are the parameters.

For the reactor building nodes represented in Figure 1 through Figure 3, Figures 4 through 6 illustrate the relative deviation as defined above between the 84th percentile PSSI spectra (x) and the deterministic FRS (y) in accordance with KTA 2201.3 for all three (3) directions. The comparison in the figures indicates that the consistency between the approaches is reasonable and the relative deviations are typically within an acceptable ±10% range in the frequency range of interest important to SSCs in the Reactor Building the (2 Hz to 40 Hz). In some cases when the deviation is greater than 10% (e.g., X response at RPV Pedestal), PSSI spectral values are larger than the corresponding DSSI values, thus indicating possible un-conservatism in the DSSI results.

A similar study reported in (Rangelow et al. (2019)) concludes that the probabilistic spectra for 84% non-exceedance probability are in good agreement with the deterministic spectra developed in accordance with KTA 2201.3. Additionally, this study also provides insights into the variation of the log standard deviations associated with the building response with the spectral frequencies. Large values of log standard deviations at the structure fundamental frequencies appear to amplify the modeling uncertainties. As the paper suggests this should be carefully considered in the fragility analysis so that the resulting HCLPFs are consistent with the deterministic proof of safety.

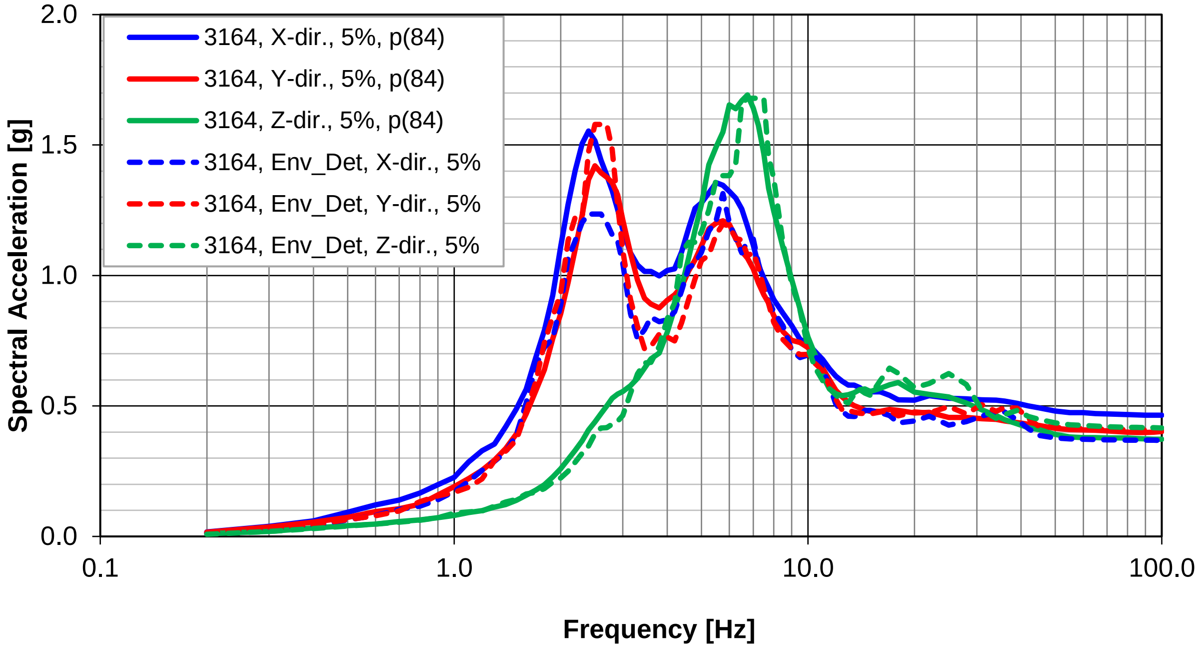

Figure 1. Comparison of DSSI and PSSI Spectra at Top of RPV Pedestal (Node 3164)

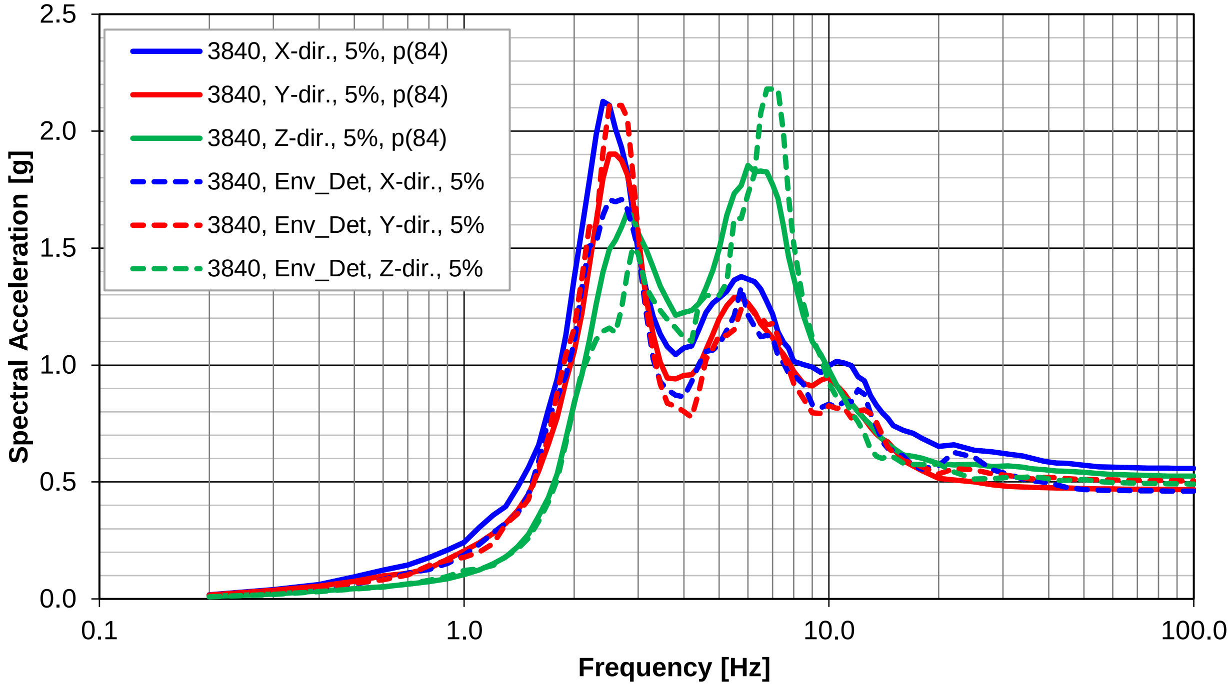

Figure 2. Comparison of DSSI and PSSI Spectra in Steam Tunnel (Node 3840)

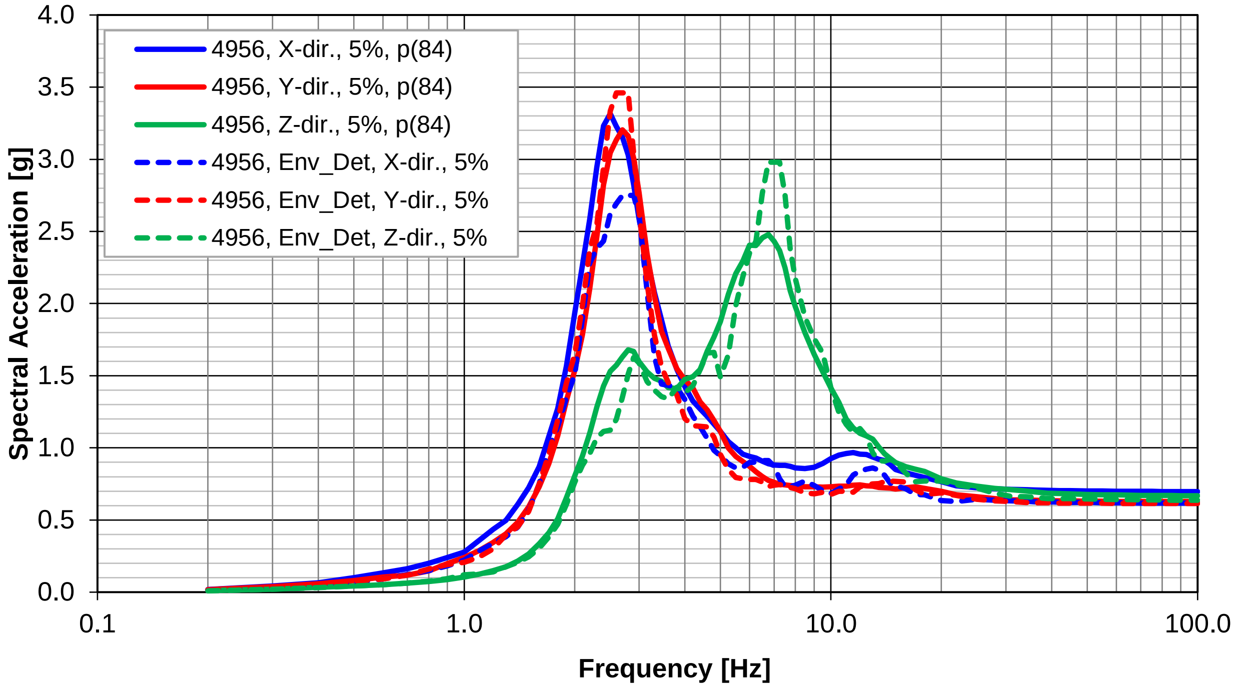

Figure 3. Comparison of DSSI and PSSI Spectra at Internal Concrete (NODE 4956)

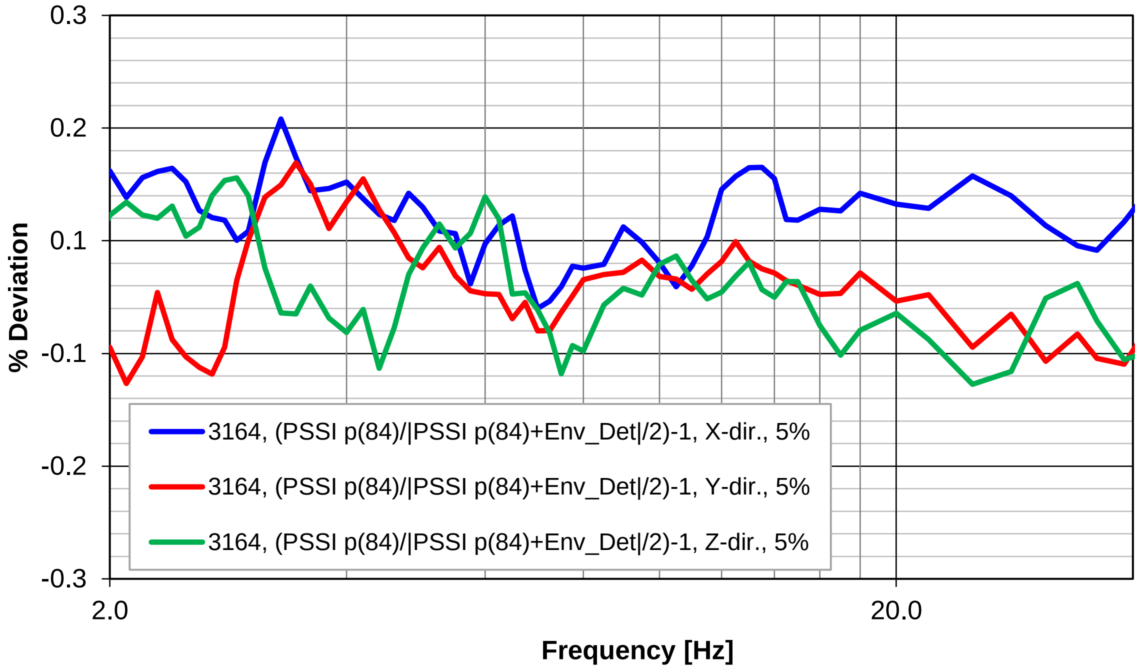

Figure 4. Relative Deviation Between DSSI and PSSI Spectra at Top of RPV Pedestal (Node 3164)

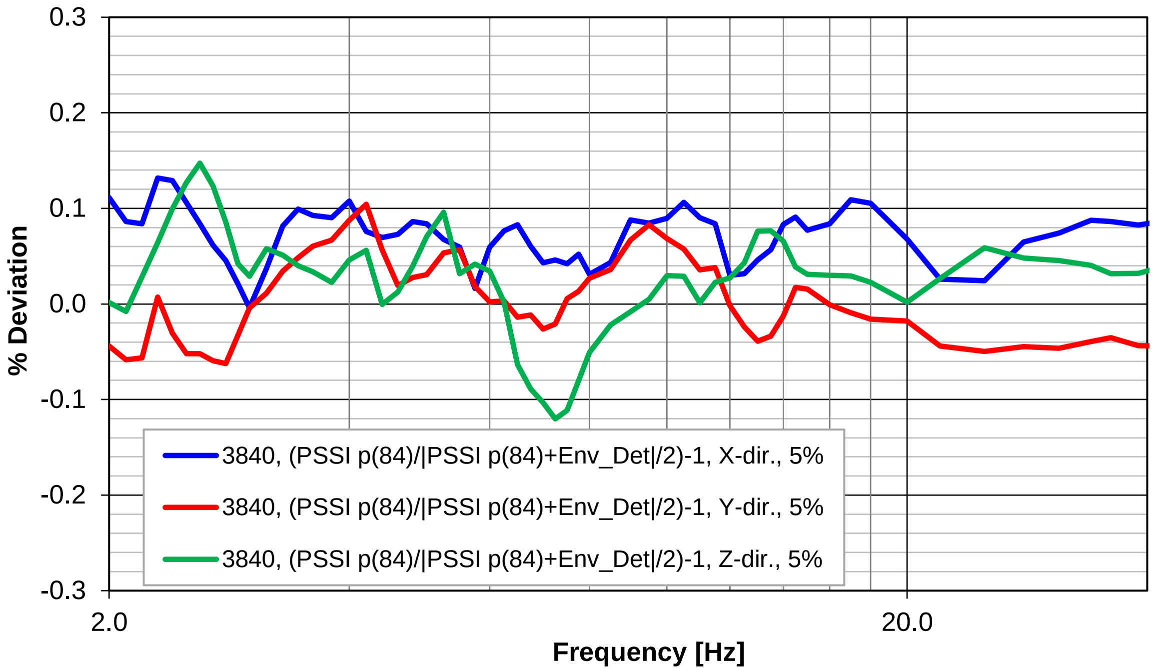

Figure 5. Relative Deviation Between DSSI and PSSI Spectra in Steam Tunnel (Node 3840)

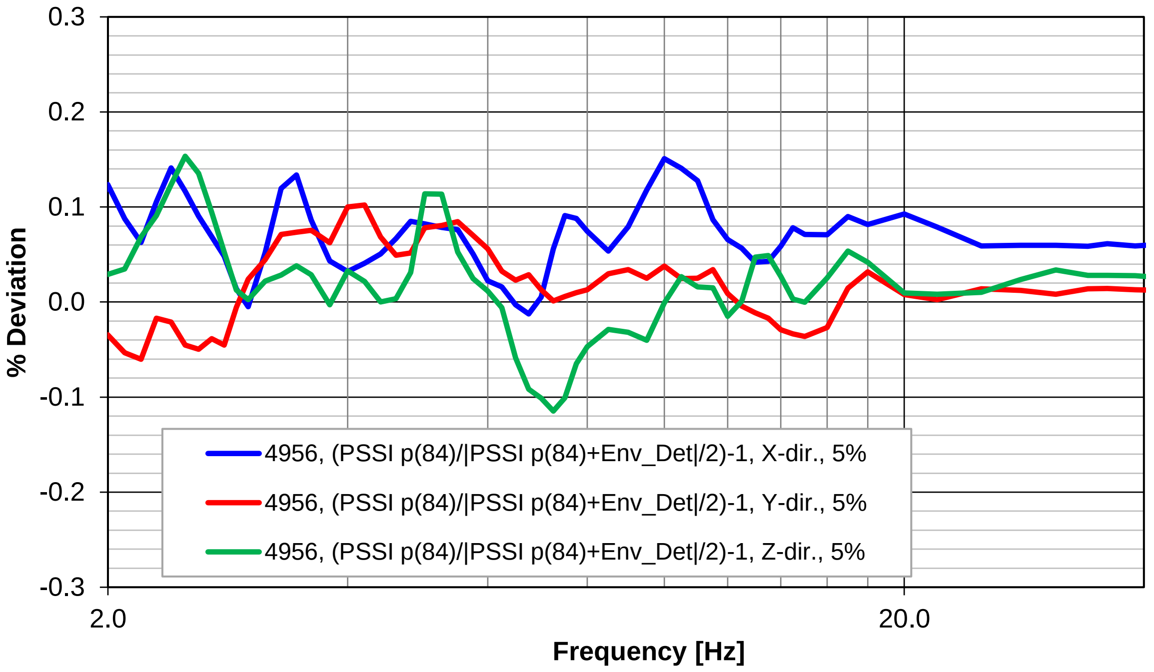

Figure 6. Relative Deviation Between DSSI and PSSI Spectra at Internal Concrete (NODE 4956)

CONCLUSION

Although the PSSI approach is significantly more resource intensive, it has been used for a NPP structures in order to reasonably ensure that the representative 84th and 50th percentile responses are used in the proof of safety analyses in accordance with the intent of ENSI-AN-8567 (2014) and with most recent standards (e.g., ASCE 4-16).

It is generally recognized that the spectral shapes of the FRS resulting from the PSSI are more representative and realistic relative to the deterministic spectra developed in accordance with KTA 2201.3. They represent equal non-exceedance probability over the full range of the frequencies of interest. The 84th non-exceedance FRS introduce sufficient conservatism to meet the quantitative performance goals.

Because the PSSI represents a more quantitative approach, established international standards allow its use to modify the deterministic FRS. According to ASCE 4-16 (ASCE 4-16 (2017)) further reductions in the deterministic spectra (using clipping) are permissible if the probability of non-exceedance for the resulting spectrum can be shown to be at least 80%. Note that the standards do not permit the modification of the PSSI responses using incomplete deterministic results.

Based on the comparisons presented in this paper, it is recommended that the 84th percentile demand (FRS) be utilized along with the 98th percentile code allowable capacity for the proof of safety analysis. The resulting seismic margins could be used as basis to define the high confidence of a low probability of failure (HCLPF) capacity characterized by the 1% probability of component failure for the given the ground motion level. The knowledge of HCLPF provides the means to demonstrate consistency between the DSA margins and fragility parameters used in subsequent seismic probabilistic risk assessment (SPRA).

The above is consistent also with Swiss guidance ENSI-AN-8567 (2014) for proof of safety verification. It is concluded that the use of the 84th percentile seismic demand developed from PSSI analysis may be sufficient to perform proof of safety verifications in lieu of calculating design basis deterministic spectra in accordance with prevalent standards. If the deterministic spectra are still needed for some applications, we also conclude that broadening maybe minimized or totally avoided if justified by supporting calculations.

Finally, yet importantly, and as recommended by IAEA in IAEA INSAG-25 (2011), the probabilistic approach aims at establishing a more uniform basis and correlation between deterministic verification and fragility analysis by using similar spectral shapes and computation technique, thus ensuring a better integration between DSA and PSA, which is notoriously a key issue in today's safety assessments.

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