TECHNICAL NOTE

On The Accuracy of Incoherency Analysis in SASSI
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Spatial incoherence of seismic waves has the effect of lowering the response of structures. This effect is more significant at higher frequencies (generally exceeding 10Hz) and with larger foundation footprints.

The purpose of this technical note is to provide a brief overview of current analytical methods in SASSI for analyzing ground motion incoherency and to recommend two new alternative procedures for addressing certain issues observed in the current methods.

Brief Overview of Current Methods

Current analytical procedures for analyzing ground motion incoherency in SASSI include the Response-SRSS, Transfer Function SRSS (TF-SRSS), Algebraic Summation (AS) and Simulation Mean (SM) Methods [1, 2, 3]. The first two are implemented at the structural response level while the latter two are implemented at the ground motion level. All four are based on deterministic analysis. The incoherent response is calculated from superposition of the modal responses associated with each significant mode of the coherency matrix having a random phase angle.

<u>Response-SRSS</u>: In this procedure, the structural response (the maximum value of motions and stresses and in-structure response spectra) at any degree-of-freedom (DOF) due to the incoherent ground motions associated with each significant mode of the coherency matrix is first calculated without including its random phase angle (i.e. assuming a phase angle of zero). Because the response associated with each mode is independent of other modes due to the orthogonality of mode shapes, the final response is calculated by taking the SRSS of the response from each significant mode.

<u>Transfer Function SRSS (TF-SRSS)</u>: In this procedure, the transfer function at any DOF of the structure from the incoherent ground motions associated with each mode of the coherency matrix is first solved without including its random phase angle (i.e. a phase angle of zero). Then for each frequency of the transfer function, the contribution of the effects of individual modes is calculated by taking the SRSS of the transfer function from individual modes. The resulting transfer function, which now includes the contribution of all significant modes, is convolved with the reference motion to calculate the time history of the response.

<u>Algebraic Summation (AS)</u>: In this procedure, the spectral factorization of the coherency matrix with a mean phase angle (i.e. a phase angle of zero) is used to calculate the incoherent ground motions at the ground motion level. The ground motion at any interaction node is calculated by algebraically summing the incoherent components of the transfer functions for all significant modes. The structural response at any DOF is then calculated by adding up the effects of input motion at all interaction nodes, and finally convolving the transfer function with the reference motion to calculate the time history of the response.

<u>Simulation Mean (SM)</u>: This procedure is very similar to the Algebraic Summation Method except that the incoherent ground motion is obtained through a simulation process involving phase angle randomization. In other words, for each significant mode of the coherency matrix, a random phase

angle is sampled between –Π and +Π and used to solve the incoherent ground motion at any interaction node. The structural response at any DOF for each simulation is then calculated by adding the contribution of input motion from all interaction nodes, and convolving the resulting transfer function with the reference motion. The final response is calculated as the mean of the response from all simulations (i.e. solution with a separate set of randomized phase angles). This procedure basically repeats the AS Method for the number of simulations performed.

Issues with Current Methods

There are some issues with all four methods described above that make them not very attractive for implementation and/or use.

Response-SRSS: The Response-SRSS Method does not generate time histories of response that may be needed to evaluate equipment or secondary systems. Therefore, it is not attractive for general applications.

TF-SRSS: Recent studies of ground motion incoherency in SASSI have revealed a numerical issue with the TF-SRSS Method. This numerical issue, further discussed below, appears to cause inaccurate and un-conservative incoherent responses in the structure.

AS and SM: As mentioned before, the AS and SM Methods combine the effects of all spectral modes at the ground motion level by assuming either a phase angle of zero or random phase angles. In either case, the results are the same: transfer functions that exhibit numerous spurious peaks from interpolation [2]. To address this problem, a large number of frequency solutions as well as numerical smoothing and conditioning of the transfer functions are required to minimize the effects of spurious peaks. This becomes a difficult task especially when dealing with detailed FE models.

With these issues in mind, it was advisable to investigate alternative and/or improved methods that would prove not only accurate but also capable of generating a time history of response while avoiding the interpolation problem.

Numerical Issue with TF-SRSS Method

Assume for one moment that we are dealing with only a single mode in the solution, in which case one would expect to obtain the same solution from the TF-STRSS Method regardless of whether SRSS was performed or not. But in fact the square root of a number has two possible values, positive and negative. Since a positive or negative sign can affect the outcome, the question becomes which sign do we use? When dealing with a single mode, it is possible to select the sign of the outcome of the square root for each frequency solution such that it is aligned with the sign of the pre-squared value to avoid this numerical issue. But it is not possible to do the same when more than one mode is involved. In other words, retaining the correct sign of the combined eigenmodes is important, and it does not seem to be doable when SRSS is performed on more than one mode, as in the TF-SRSS Method. As a side note, the use of SRSS in the Response-SRSS Method is valid because it is applied at the final response level for each spectral mode (similar to modal superposition time history analysis) rather than at the transfer function level. As a result, the orthogonality of the mode shapes remains valid.

New Alternative Methods

To address the above concerns, two new alternative methods of incoherency analysis in SASSI have been investigated: the TF-Summation and Response-Simulation Methods.

<u>TF-Summation</u>: This procedure was developed to address the numerical issue associated with the TF-SRSS Method. The new TF-Summation Method is similar to TF-SRSS except, after solving for each significant mode of the coherency matrix with a phase angle of zero, the contribution of the effects of the individual modes at any DOF in the structure is calculated by algebraic summation rather than taking the SRSS of the transfer functions from individual modes. It reflects the mean input while eliminating the possibility of more than one numerical outcome.

<u>Response-Simulation</u>: This new procedure basically repeats the TF-Summation Method for multiple simulations, each using a random phase angle rather than a phase angle of zero for each significant mode of the coherency matrix. The final result is then obtained by taking the mean of all the simulations.

The newly implemented TF-Summation and Response-Simulation Methods have a key advantage. The calculated transfer functions from each simulation (with TF-Summation being just one simulation with a zero phase angle) are not affected by spurious peaks from interpolation because the spectral mode shapes of the coherency matrix are better suited for individual input to the SSI model rather than being combined into one input at the ground motion level, as is the case with the AS and SM procedures.

The TF-Summation and Response-Simulation Methods require the same numerical effort as the TF-SRSS Method controlled by the number of significant modes to be solved. Response-Simulation does not require any significant additional effort because each simulation is part of the post-processing effort.

Test Problems

To assess the accuracy of the TF-SRSS, TF-Summation and Response-Simulation Methods implemented in MTR/SASSI, three test problems were performed and the results presented below. In all three cases the structure is supported at the ground surface on hard rock. The input motion consists of three orthogonal components of acceleration time histories spectrally matched to high-frequency hard rock (HFHR) uniform hazard spectra (UHS). Spatial incoherency of the ground motion is characterized by hard rock coherency functions. All incoherent results are obtained for 10 significant modes of the coherency matrix and 20 simulations for the Response-Simulation Method.

Problem 1

Test problem 1 is shown in Figure 1a. It depicts a stick model of a nuclear plant similar to the model used in [3].

Figures 1b, 1c and 1d show comparisons of the incoherent acceleration response spectra at the top of the ASB stick in the x-, y- and z-directions, respectively, calculated from the TF-SRSS, TF-Summation and Response-Simulation Methods together with the target incoherent response spectra from stochastic analysis using CLASSI. The calculated coherent response is also shown for reference. As seen in Figures 1c and 1d, the TF-SRSS results fall significantly below the target results (the stochastic solution obtained from CLASSI) at significant modes of the structure in the y- and z-directions. The results from TF-Summation underestimate the response at frequencies above 9Hz in the x-direction (Figure 1b) and overestimate the response at frequencies of 3-5Hz in the y-direction (Figure 1c). The Response-Simulation results show excellent agreement with the target solution.

Problem 2

Test problem 2 is shown in Figure 2a. It depicts a stick model of a nuclear structure.

As shown in Figures 2b, 2c and 2d, the TF-SRSS Method again underestimates the spectral response at high frequencies in all three directions, including at the peak. The TF-Summation and Response-Simulation Methods show good agreement except that TF-Summation underestimates the spectral response at low frequencies in the z-direction (Figure 2d).

Problem 3

Test problem 3 is shown in Figure 3a. It depicts a finite element model of the same structure shown in Figure 2a.

Again, TF-SRSS underestimates the spectral response, including at the peak of the spectra above 10Hz in the x- and z-directions and above 8Hz in the y-direction. TF-Summation and Response-Simulation show relatively good agreement at all frequencies except at the second peak of the spectra in the y-direction where TF-Simulation shows a slightly lower shifted peak.

Conclusions

The TF-SRSS Method appears to underestimate the in-structure response spectra for both the stick and detailed FE models. The new TF-Summation Method provides reasonably accurate results for the stick and detailed FE models at most locations. However, some anomalous results from the TF-Summation Method have been observed in the detailed FE model and are currently being further investigated. The Response-Simulation Method provided the most accurate and reliable results for both the stick and detailed FE models at all locations.

Because all three methods require about the same level of numerical effort, the Response-Simulation Method is considered the preferred option for analyzing ground motion incoherency in SASSI. Also note that no smoothing or conditioning of transfer functions was required with the new procedures.

References

1. EPRI (1997). “Soil-Structure Interaction Analysis Incorporating Spatial Incoherence of Ground Motions,” Electric Power Research Institute, Palo Alto, USA, TR-102631.
2. EPRI (2007a). “Program on Technology Innovation: Effects of Spatial Incoherence on Seismic Ground Motions,” Electric Power Research Institute, Palo Alto, USA, TR-1015110.
3. EPRI (2007b). “Program on Technology Innovation: Validation of CLASSI and SASSI Codes to Treat Seismic Wave Incoherence in Soil-Structure Interaction (SSI) Analysis of Nuclear Power Plant Structures,” Electric Power Research Institute, Palo Alto, USA, TR-1015111.

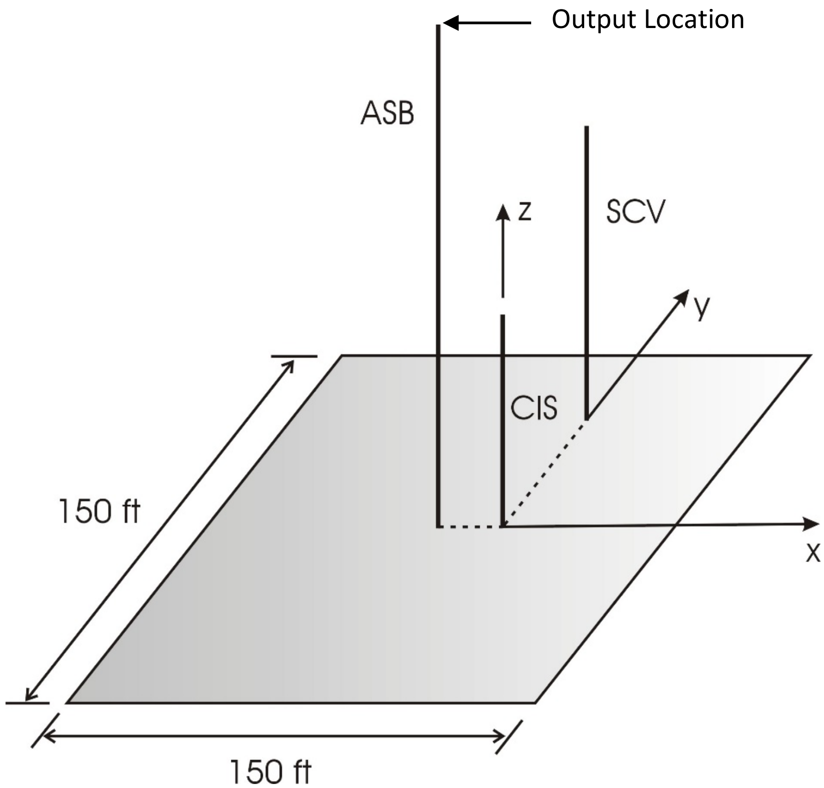

Figure 1a. Nuclear Plant Stick Model 1

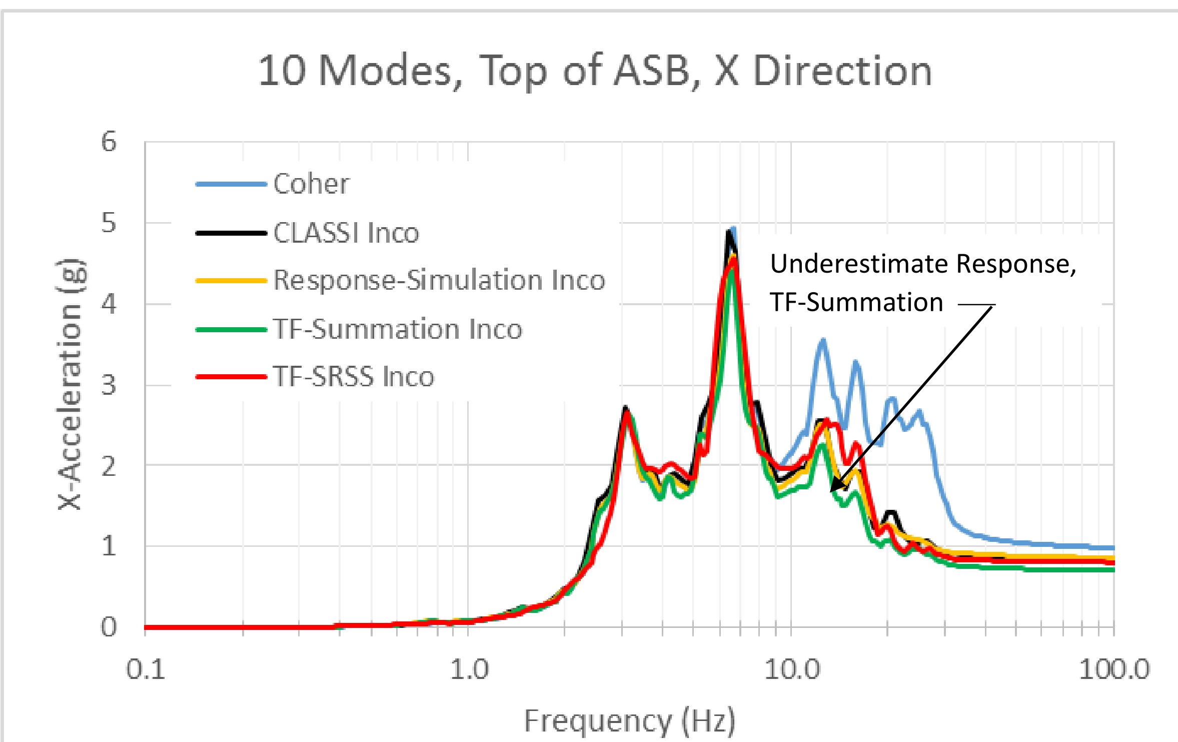

Figure 1b. Comparison of 5%-Damped Spectra at Top of ASB, Model 1, X-Dir.

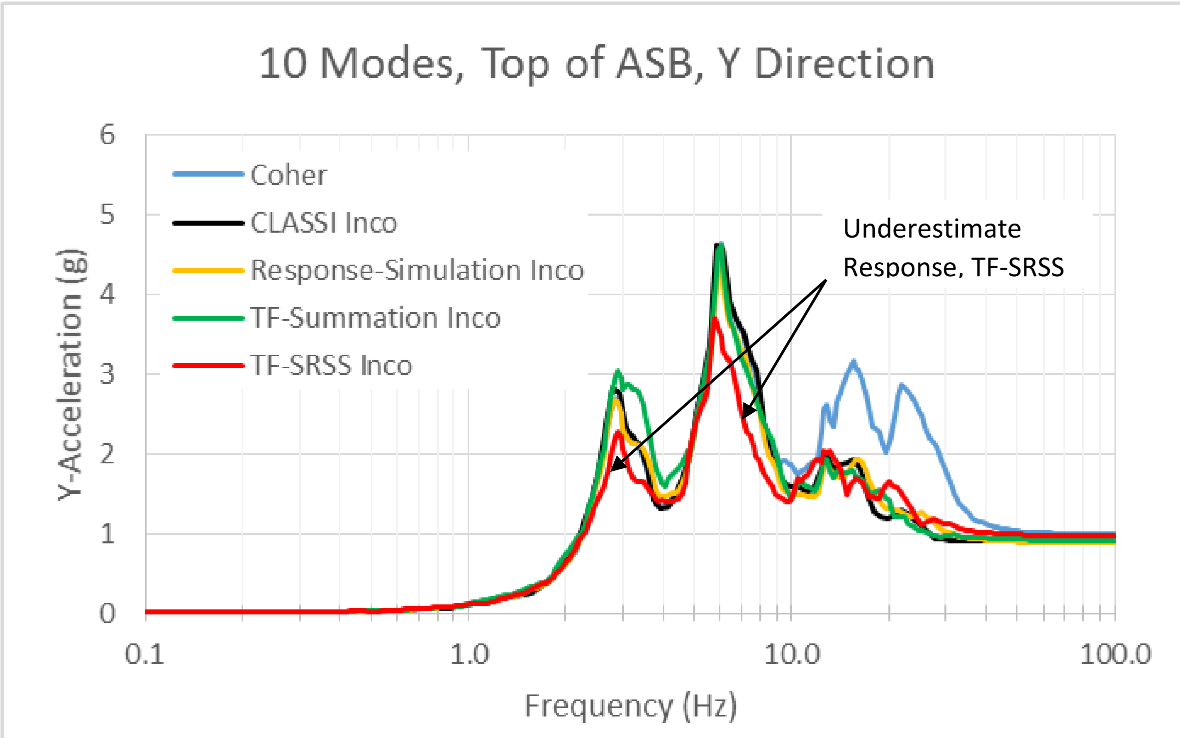

Figure 1c. Comparison of 5%-Damped Spectra at Top of ASB, Model 1, Y-Dir.

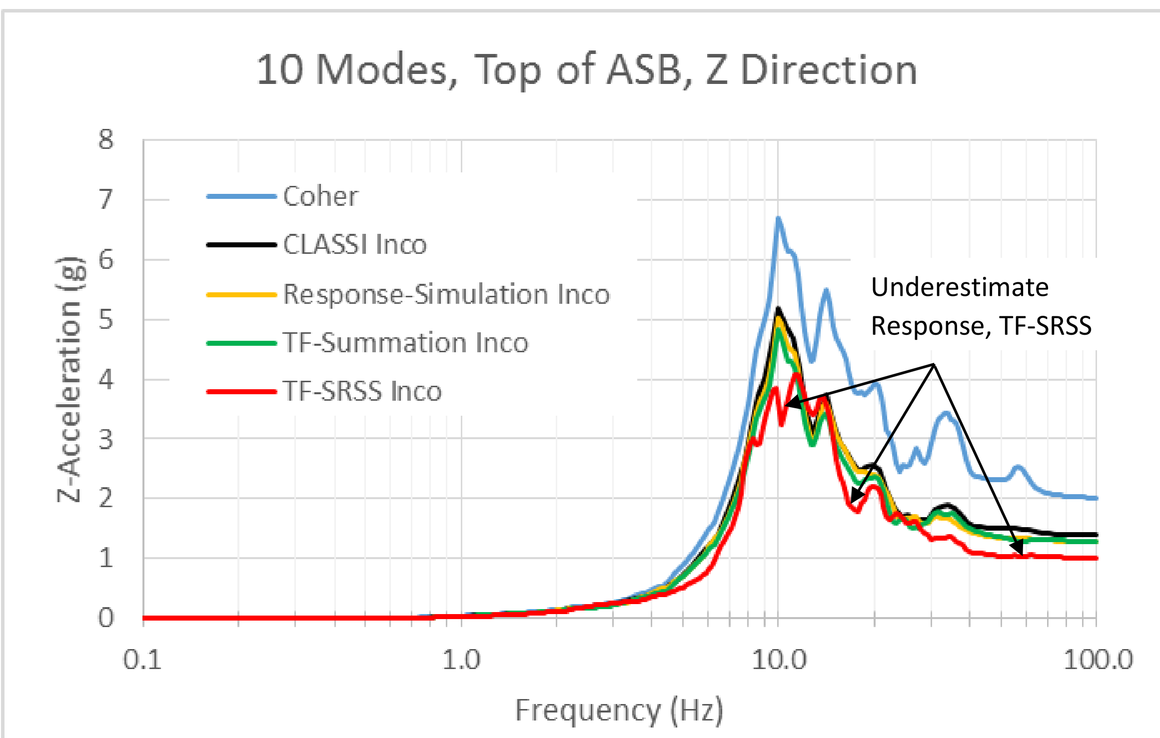

Figure 1d. Comparison of 5%-Damped Spectra at Top of ASB, Model 1, Z-Dir.

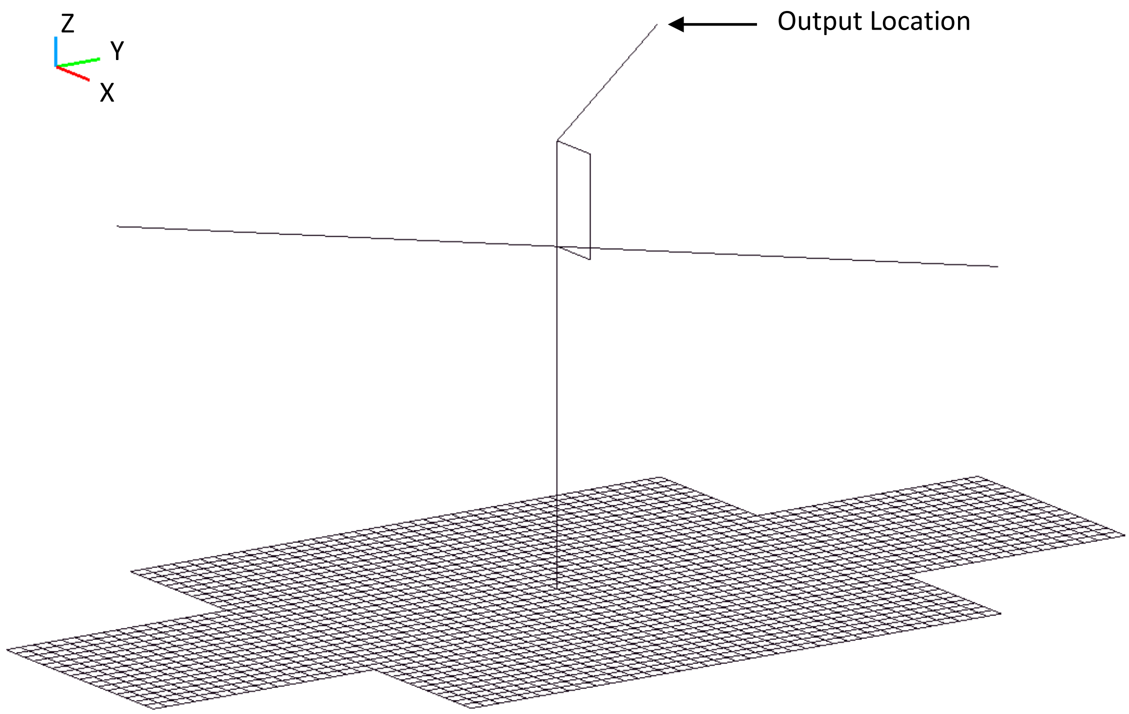

Figure 2a. Nuclear Plant Stick Model 2

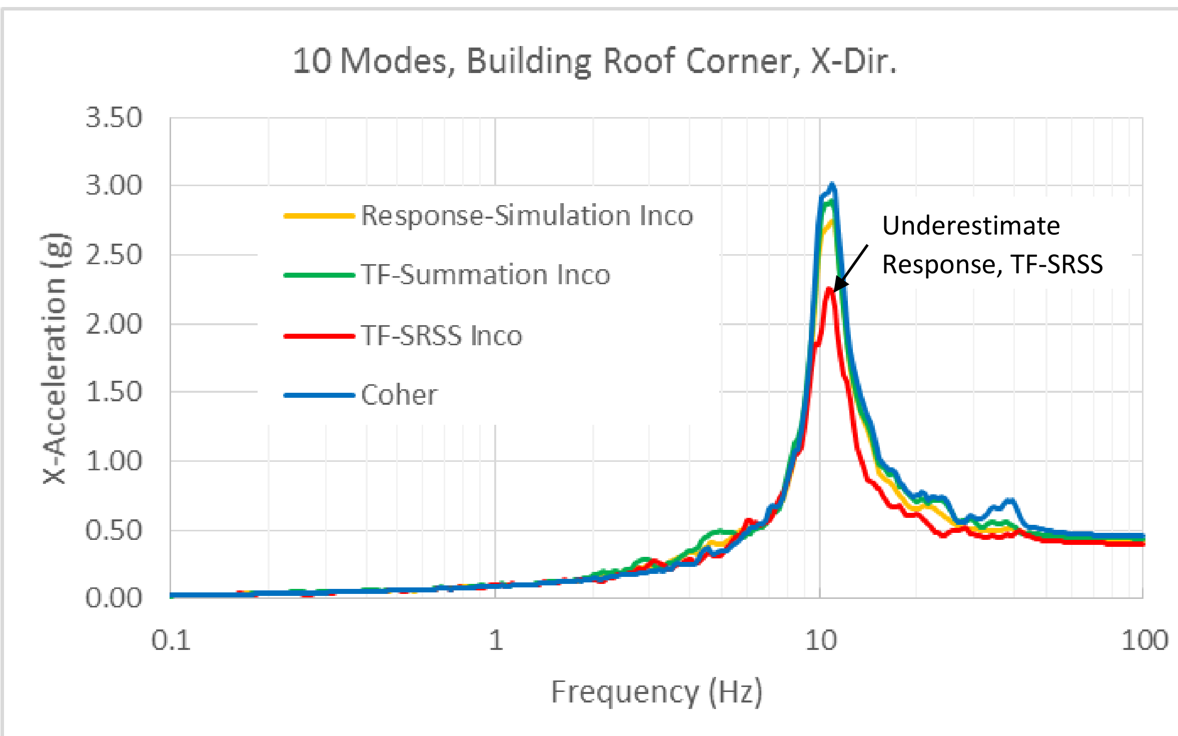

Figure 2b. Comparison of 5%-Damped Spectra at Building Roof Corner, Model 2, X-Dir.

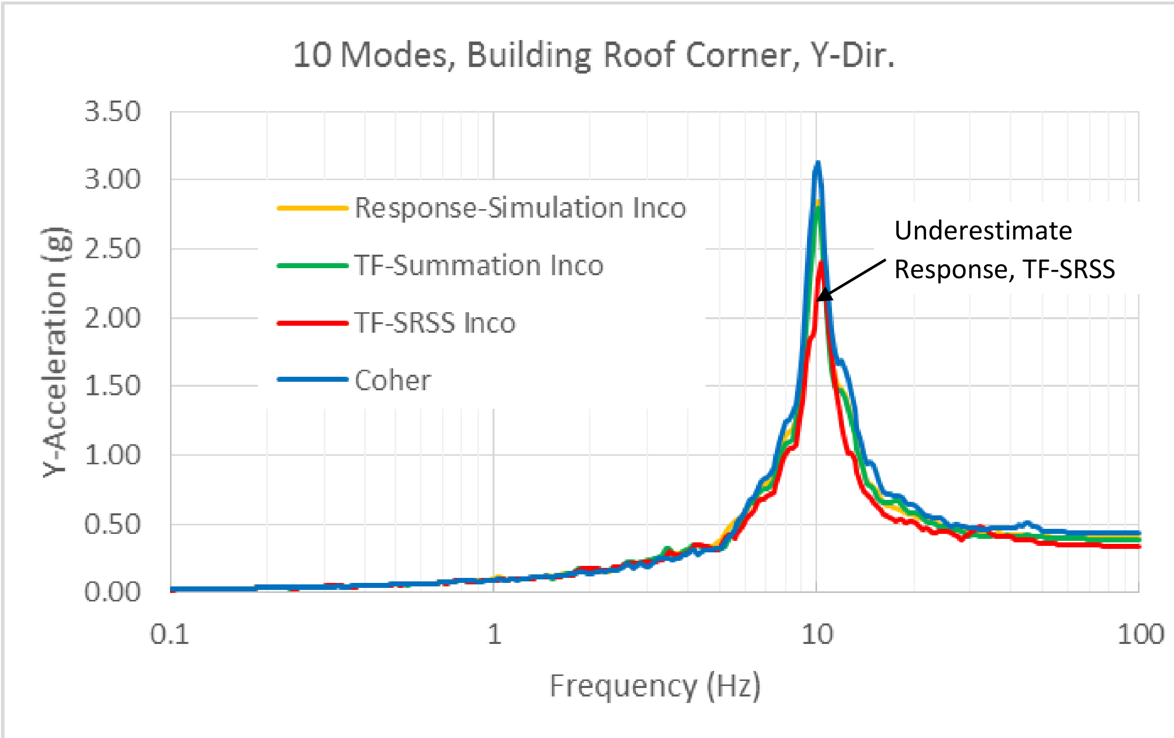

Figure 2c. Comparison of 5%-Damped Spectra at Building Roof Corner, Model 2, Y-Dir.

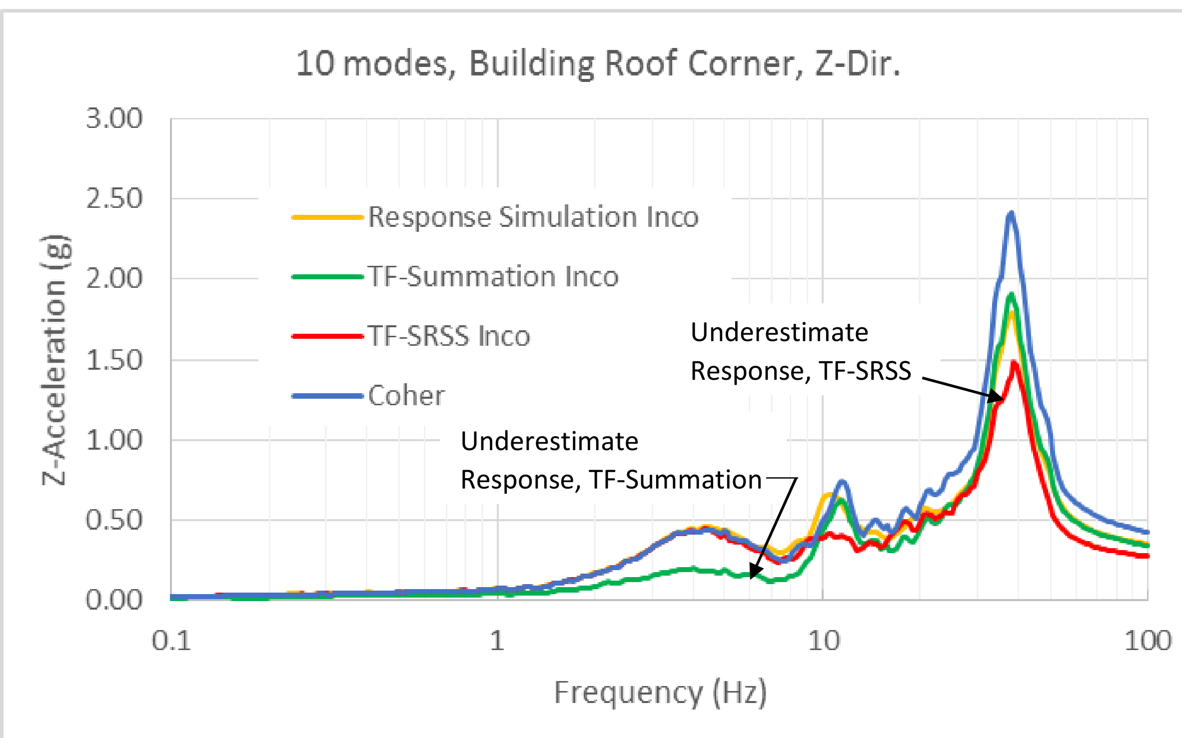

Figure 2d. Comparison of 5%-Damped Spectra at Building Roof Corner, Model 2, Z-Dir.

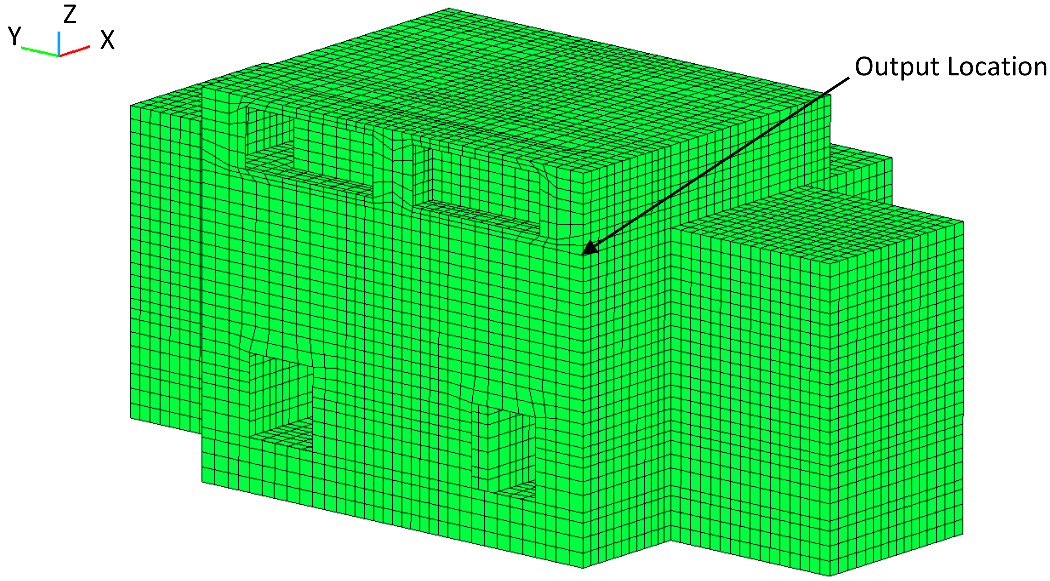

Figure 3a. Nuclear Plant Finite Element Model 3

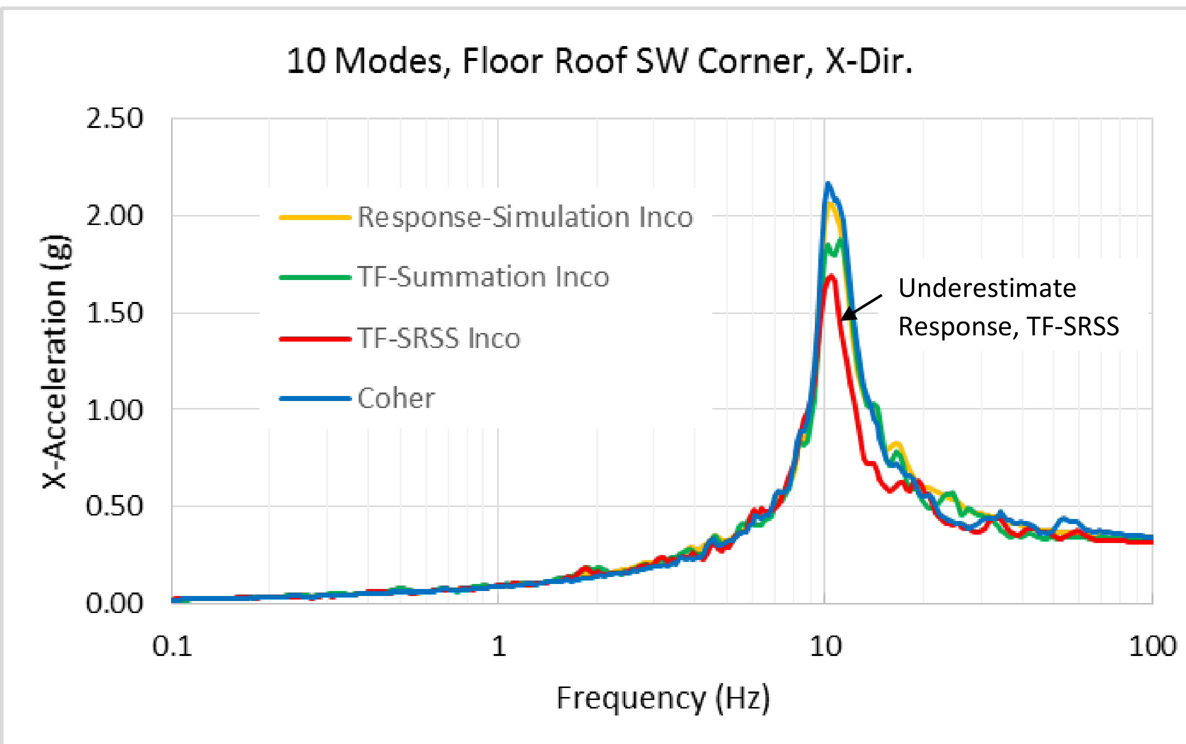

Figure 3b. Comparison of 5%-Damped Spectra at Floor Roof SW Corner, Model 3, X-Dir.

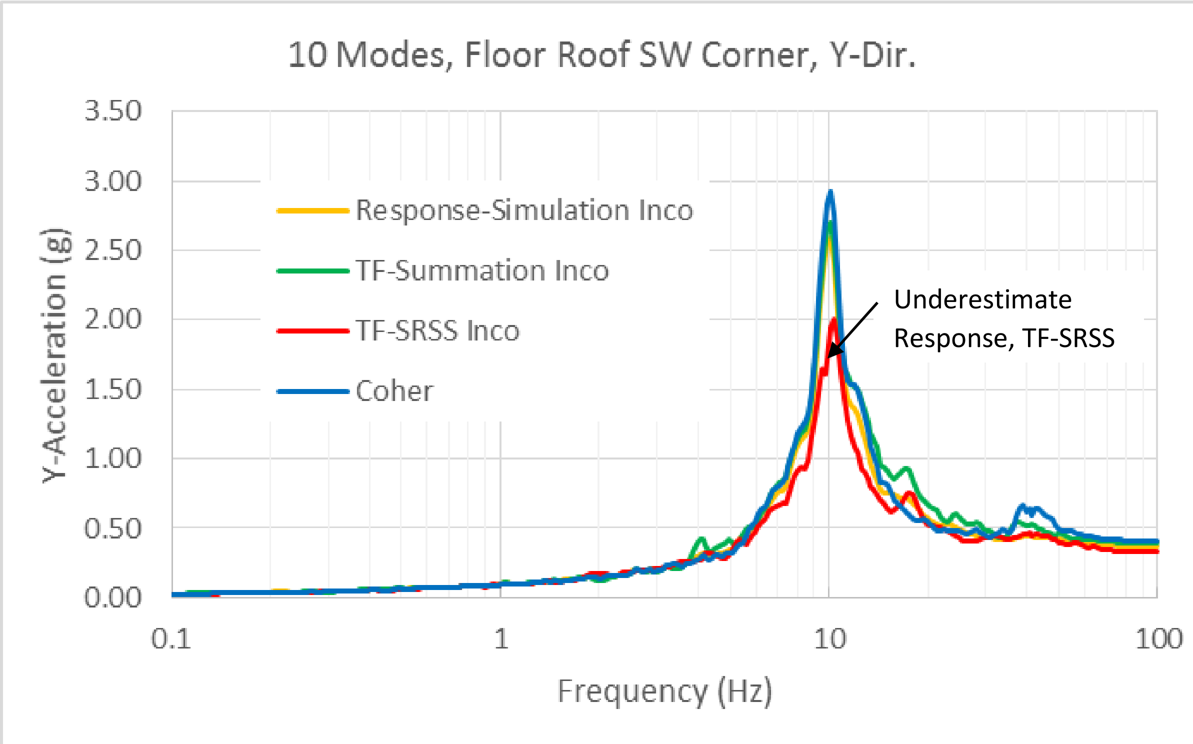

Figure 3c. Comparison of 5%-Damped Spectra at Floor Roof SW Corner, Model 3, Y-Dir.

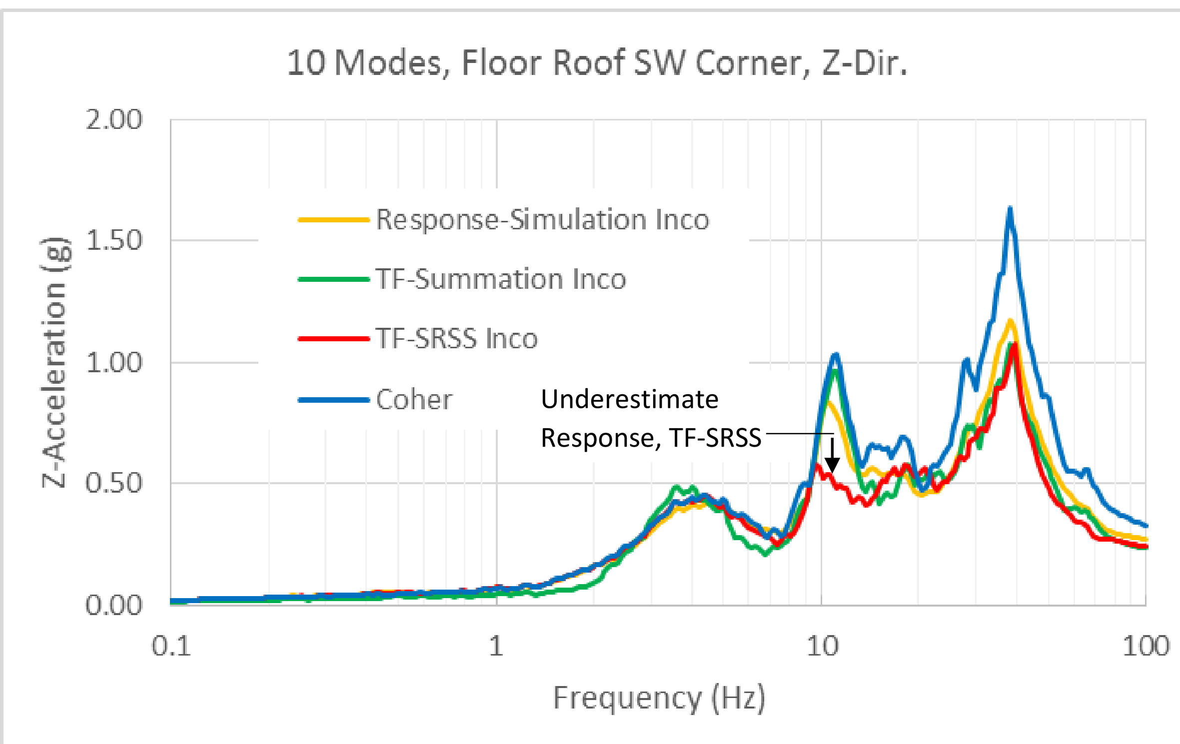

Figure 3d. Comparison of 5%-Damped Spectra at Floor Roof SW Corner, Model 3, Z-Dir.