20th International Conference on Structural Mechanics in Reactor Technology (SMiRT 20)
Espoo, Finland, August 9-14, 2009
SMiRT 20-Division K, Paper 1853

Seismic Motion Incoherency Effects on SSI Response of Nuclear Islands with Significant Mass Eccentricities and Different Embedment Levels

Dan M. Ghiocel[a], Stephen Short[b] and Greg Hardy [b]

[a]Ghiocel Predictive Technologies, Inc., 6 South Main St., Pittsford, New York 14534, USA
e-mail: dan.ghiocel@ghiocel-tech.com
[b]Simpson, Gumpertz and Heger,4000 MacArthur Blvd.,7th Floor, Suite 710, Newport Beach, California 92660, USA

Keywords: soil-structure interaction, motion incoherency, incoherent, rock site, nuclear island, seismic.

1 ABSTRACT

The paper shows the effects of seismic motion incoherency on the soil-structure interaction (SSI) response of a nuclear structures founded on different site conditions. The paper presents results obtained from a sequence of parametric SSI studies using the AP1000-based stick SSI model that was also employed in recent EPRI studies (Short, Hardy, Merz and Johnson, 2006 and 2007). The paper focuses on the effects of foundation embedment on incoherent SSI response. Different stochastic and deterministic incoherent SSI approaches are employed. These incoherent SSI approaches are a part of those used in the EPRI studies called the SASSI-based approaches (deterministic AS and SRSS approaches, and stochastic simulation approach). In addition, an alternate version of the SRSS approach is included. The 2005 and 2007 Abrahamson incoherency models for all sites, hard-rock sites and soil sites are applied. No wave passage effects are considered. The computed SSI results show that incoherent SSI effects are significant for both non-embedded and embedded structures. Conclusions and recommendations are stated at the end of the paper.

2 SEISMIC MOTION INCOHERENCY

Seismic motion incoherency is due to the local spatial random variations of the seismic ground motion in horizontal plane across building foundations as a result of wave scattering and wave passage effects. Assuming that the ground motion stochastic spatial variations in horizontal plane can be idealized by a stationary Gaussian stochastic field, then, its spatial correlation structure is completely defined by its coherency spectrum, or coherence function. More generally, the coherence function is a complex quantity, often called in earthquake engineering literature the “unlagged” coherence function (Abrahamson, 2007). However, in practice, the “lagged” coherence function, that is real and positive quantity defined by the amplitude of the complex coherence function is used. If the horizontal apparent wave velocity of the wave passge term is considered to be constant for all frequencies, then the “plane-wave” coherency model is defined. The plane-wave coherency models could be used in conjunction with the plane-wave propagation SSI codes, as it is illustrated herein.

It should be noted that the coherence function at any given frequency is identical with the statistical correlation coefficient or scaled covariance between two random variables that are defined by the amplitude of the motion at two different locations. This observation suggests that a series of efficient engineering numerical tools developed for digital simulation of stochastic spatial variation fields based on factorization of covariance kernels could be extended for simulation of seismic motion spatial variation fields using factorization of coherence kernels at each frequency.

Currently, based on significant statistical database information, motion incoherency models were defined by a set of specific coherency functions for different soil conditions and foundation levels for 1) all sites and shallow foundations (Abrahamson, 2005), 2) all sites and embedded foundations (Abrahamson, 2006), 3) specific for hard-rock sites and shallow of embedded foundations (Abrahamson, 2007) and 4) specific soil sites for shallow foundations (Abrahamson, 2007). The coherency function is unity for coherent SSI analysis. The coherence function is near unity at low frequencies (less than 5 Hz) and reduces with frequency and separation distance between the observation points in the free-field.

3 INCOHERENT SSI ANALYSIS METHODOLOGY

Two types of incoherent seismic SSI analysis approaches could be used: the stochastic approach and deterministic approach. These approaches were investigated by Short, Hardy, Merz and Johnson (2007). *Stochastic approach* is based simulating random incoherent motion realizations (called Simulation Mean in EPRI studies). Using stochastic simulation algorithms, a set of random incoherent motion samples is generated at each foundation SSI interaction nodes. For each incoherent motion random sample an incoherent SSI analysis is performed. The final mean SSI response is obtained by statistical averaging of SSI response random samples. *Deterministic approach* approximates the mean incoherent SSI response using simple superposition rules of random incoherency mode effects, such as the algebraic sum (called AS in EPRI studies) and the square-root of sum of squares (called SRSS in EPRI studies).

It should be noted that for the stochastic simulation approach and the deterministic approach based on linear superposition, the number of extracted coherency matrix eigenvectors, or incoherent spatial modes, can be as large as desired with zero impact on the incoherent SSI analysis run time. By default, all the incoherent spatial modes are included. Consideration of all incoherent spatial modes improves the incoherent SSI accuracy and produces an accurate recovery of the free-field coherency matrix at the interaction nodes; this can be checked for each calculation frequency. The AS approach is fast, few times faster than the stochastic approach, and it is easy to use.

Herein, we considered both stochastic and deterministic incoherent SSI approaches using the ACS SASSI code (Ghiocel, 2007 and 2009). In addition to the stochastic simulation apprach, three deterministic approaches were considered: i) linear superposition, or algebraic sum, of the scaled incoherent spatial modes (AS in EPRI studies), ii) quadratic superposition of the incoherent modal SSI complex response amplitudes (transfer function amplitudes) assuming a zero-phase for the incoherent SSI complex response phase (SRSS in EPRI studies), and iii) quadratic superpostion of the incoherent modal SSI complex response amplitudes (transfer function amplitudes) assuming a non-zero phase for the incoherent SSI complex response that is equal to coherent SSI complex response phase (not used in EPRI studies). The last implementation is an alternate version of SRSS approach that does not neglect the complex response phase.

4 CASE STUDIES

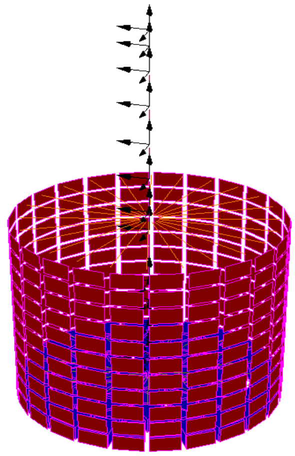
Two case studies are considered: i) A typical PWR Reactor Building (RB) with three different embedment levels, and ii) the AP1000-based stick model used in the EPRI studies with different embedment levels, and two different foundation mat sizes. The AP1000-based stick model that was surface founded in the EPRI studies was embedded in the analyses of this paper. The two embedded structural models are shown in Figures 1 and 2. The embedded foundation walls are modeled by shell elements.

Seismic input and soil layering were assumed: i) identical with those used in EPRI studies for AP1000-based stick model, ii) typical hard-rock site-specific GRS with 2007 Abrahamson hard-rock coherency model and hard-rock soil profile with Vs of 9000 fps, iii) RG 1.60 GRS with 2007 Abrahamson soil coherency model and soil layering with Vs of 1000 fps.

4.1 RB SSI Model

The embedment levels were 0 ft and 50 ft. Seismic input and soil layering that were used in EPRI studies were considered. The RB foundation diameter was 130ft. Three incoherent SSI approaches were applied.

The effect of embedment is shown in Figure 3. It should be noted that the motion incoherency effects are larger for embedded foundation than for non-embedded foundation. This is due to the increase in the dominant SSI mode frequency of the RB structure shifts from 7 Hz for non-embedded foundation to 10 Hz for embedded foundation. Incoherencu is more pronounced with increasing frequency.



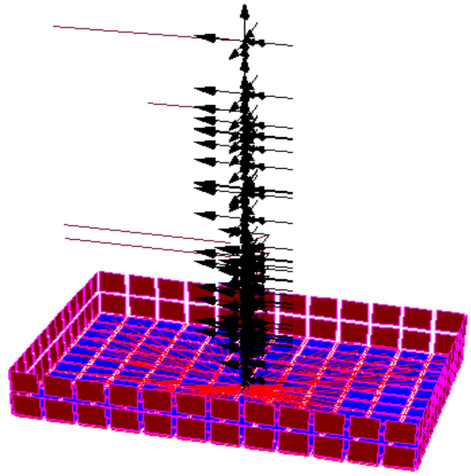


Figure 1 Embedded RB Model

Figure 2 Embedded AP1000-based Stick Model

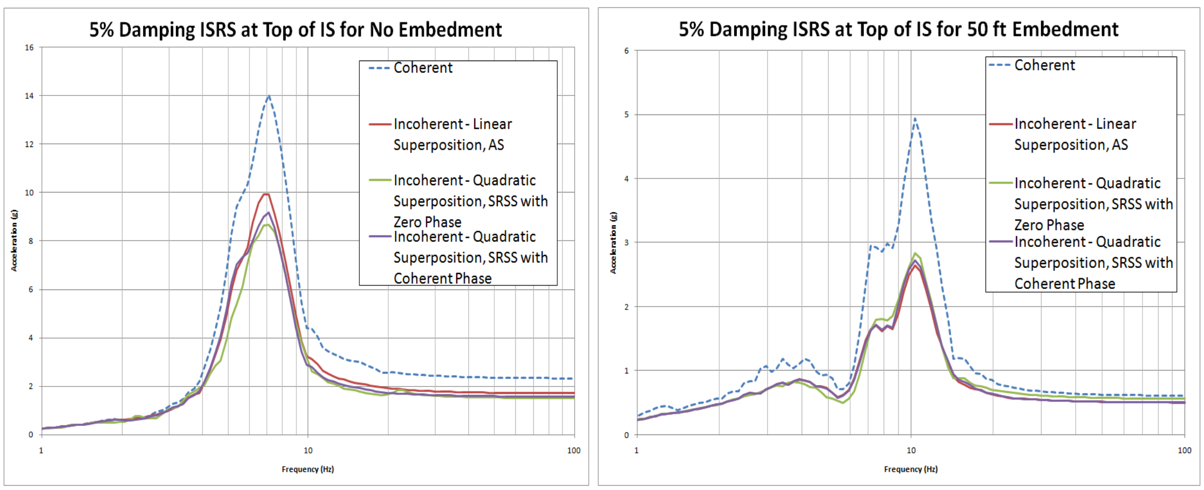


Figure 3 Embedment Effects on the Coherent and Incoherent ISRS Computed at Top of RB Structure

In either case shown in Figure 3, there is a significant reduction of response relative to coherent SSI.

4.2 AP1000-Based Stick Model

In this study, we used two versions of the AP1000-based stick model: i) the Original model that is exactly that used in EPRI studies (Short, Hardy, Merz and Johnson, 2007) and ii) a Modified model to reflect the real horizontal foundation size of the actual AP1000 nuclear island complex with two different soil contions. Thus, the AP1000-based stick foundation size was modified from the 150ft x 150ft size used in the EPRI investigations to the 158ft x 254ft size that is in the actual design, as shown in Figure 2.

For the original AP1000-based stick model, the soil layering, seismic input and Abrahamson coherency model were identical with those used as in the EPRI studies. For the modified AP1000-based stick model with a larger foundation size, the seismic input and soil layering were changed to reflect two extreme soil site conditions: 1) hard-rock site (Vs about 9000fps) and 2) soft soil condition (Vs about 1000fps). The seismic input was defined by a site-specific ground spectrum that is typical for the hard-rock condition (peak spectral acceleration is in the 20-25 Hz range), and the RG 1.60 spectrum for the soil condition, respectively. The 2007 Abrahamson coherency model for hard-rock and soil sites were applied (incoherency model options # 5 and 6, respectively, in ACS SASSI). The control motion was defined at ground surface.

The two versions of the AP1000-based stick models were considered with no embedment, as in EPRI studies, and with 35 ft and 50 ft embedment depths, respectively.

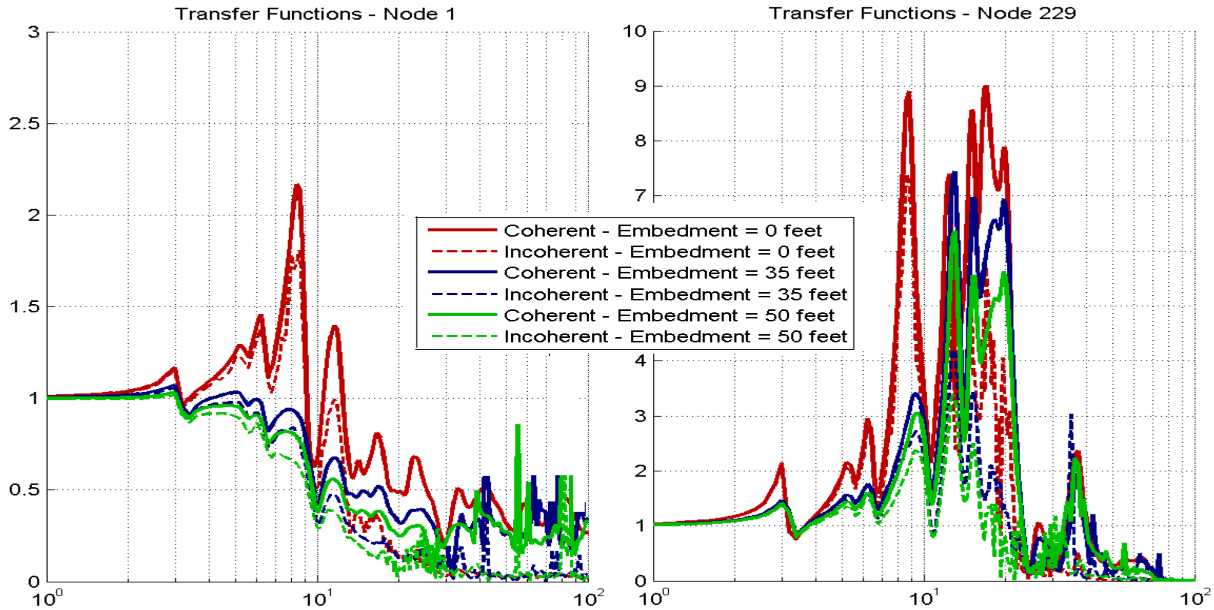


Figure 4. Embedment and Motion Incoherency Effects on Acceleration Transfer Function (ATF) Amplitudes at Basemat Center (Node 1) and at the Top of CIS (Node 229)

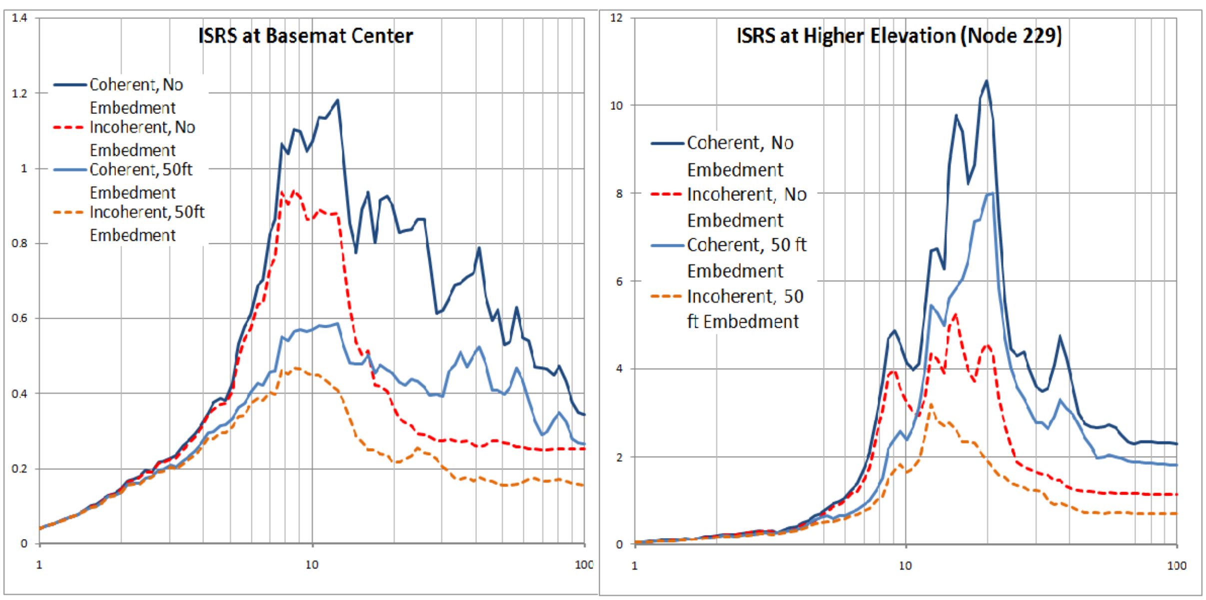


Figure 5 Embedment and Motion Incoherency Effects on 5% Damping ISRS at Basemat Center (Node 1) and at the Top of CIS (Node 229)

Figures 4 and 5 show the computed (mean) incoherent and coherent acceleration transfer function amplitudes and 5% damping ISRS in the X direction at the basemat center (node 1) and at the outrigger extending 75ft in X direction from the top of the containment internal structure (CIS) of the unmodified EPRI AP1000-based stick model (node 229). The same seismic input and soft rock layering used in the EPRI studies was considered. Comparisons are for no embedment, 35ft and 50ft embedments. The 2005 Abrahamson coherency model developed for all sites was employed for both non-embedded and embedded SSI models.

It should be noted that the favorable embedment effects to reduce the SSI responses are dominant up to 12-15 Hz frequency, above which the motion incoherency effects become more dominant. As shown in Figure 5, in the high-frequency range the ISRS reductions due to motion incoherency could be more than 50%.

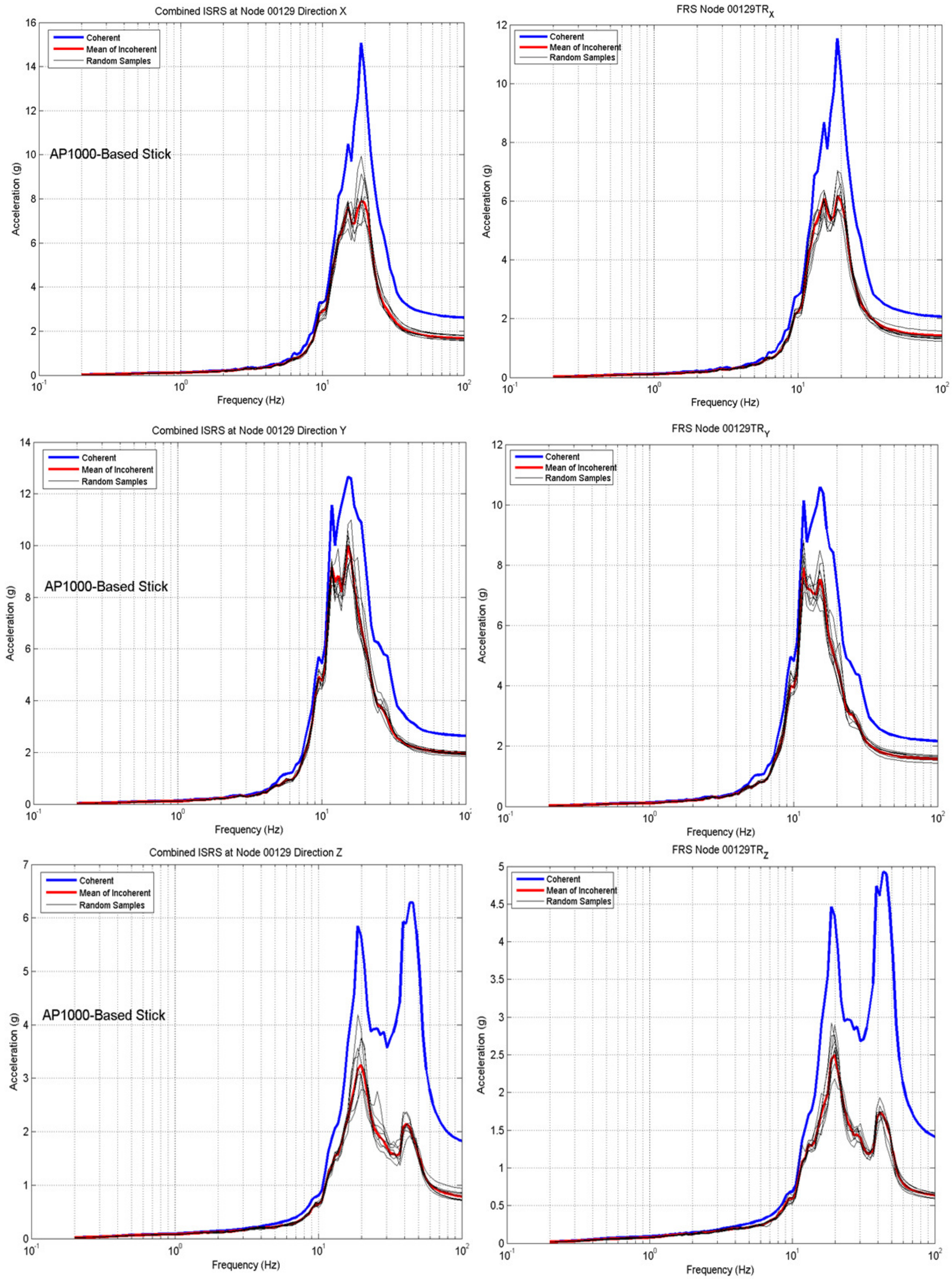


Figure 6 Motion Incoherency Effects for Non-Embedded (left plots) and 40ft Embedded (right plots) AP1000-based Stick on 5% Damping ISRS at Top of CIS for the Hard-Rock Conditions (Vs of 9000fps) with the Hard-Rock Seismic Input for X (top), Y(center) and Z (bottom) Directions.

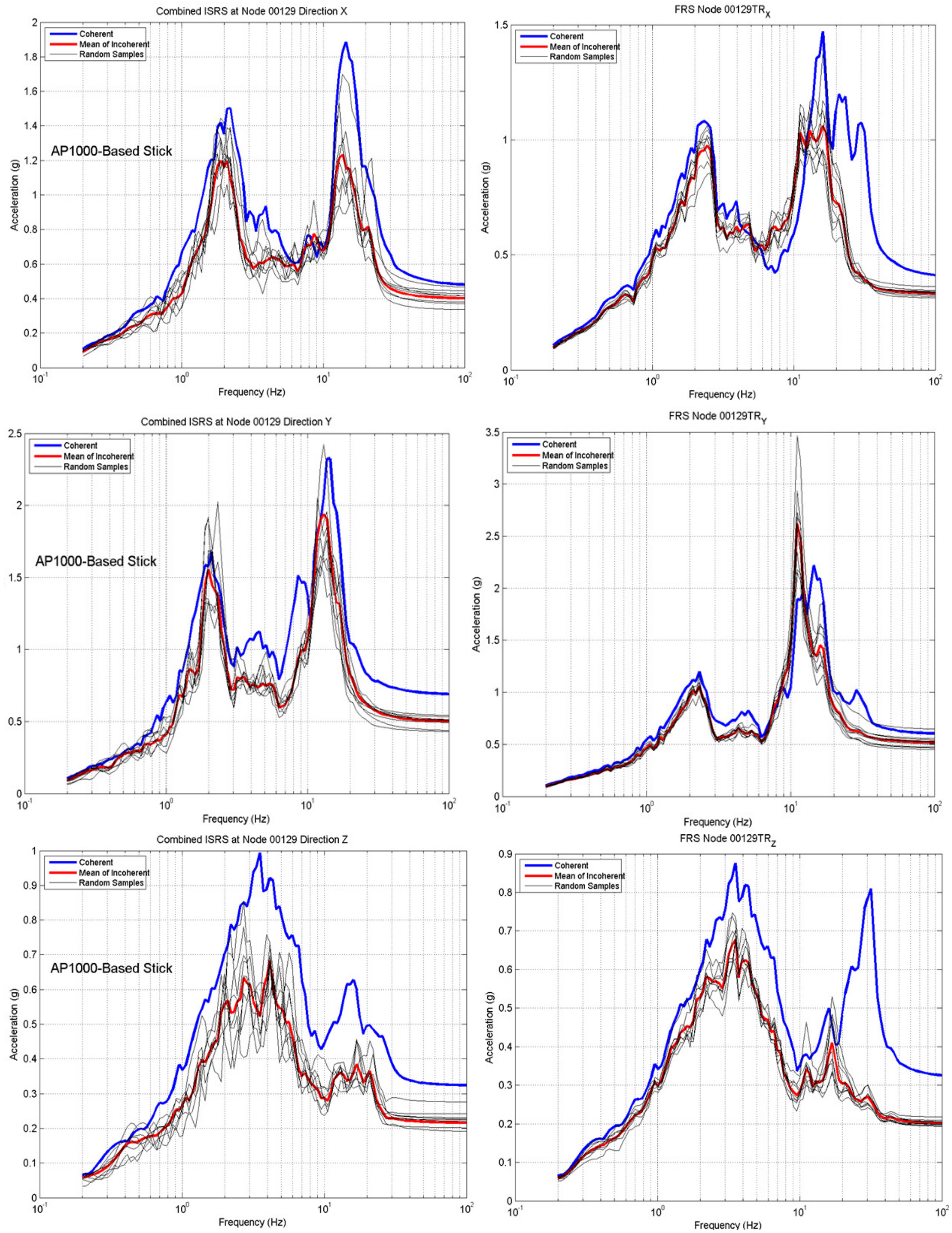


Figure 7 Motion Incoherency Effects for Non-Embedded (left plots) and 40ft Embedded (right plots) AP1000-based Stick on 5% Damping ISRS at Top of CIS for the Soft Soil Conditions (Vs of 1000fps) with the RG 1.60 Seismic Input for X (top), Y(center) and Z (bottom) Directions

Figures 6 and 7 show the effect on motion incoherency on the 5% damping ISRS computed for the modified AP1000-based stick model, at the outrigger extending 10 ft in Y direction from the top of CIS (node 129) for both hard-rock and soft-soil site conditions. The SSI analysis inputs for the two site conditions, including the coherence functions, are described in section 4.2.

By studying Figures 6 and 7, there are several visible aspects that need to be remarked:

- The effects embedment and motion incoherency on SSI responses are significant for both the hard-rock and soft-soil sites. It should be noted that even for the hard-rock site with Vs of 9,000fps (about 3,000m/s), the embedment effect still produces a 20% ISRS reduction. More generally, the motion incoherency effects are significantly larger for hard-rock sites than soil-sites. However, as shown in Figure 7 for ISRS in Z-direction, the reduction due incoherence could be also large for soil sites if higher frequency responses are present.

- The effects of embedment and motion incoherency on SSI response have simple trends for the hard-rock condition and complex trends for the soft-soil condition. For soft soil condition, the embedment effect indicates a slightly different dynamic behavior of the SSI model that is visible under both coherent and incoherent inputs. For example, in the X and Z directions, the coherent ISRS show that the embedment amplifies the SSI mode responses at 25 Hz and 30 Hz frequencies. Also, the torsional SSI mode sthat shows in the 12-14 Hz frequency range in Y-direction response is clearly more amplified by the motion incoherency for the embedded SSI model than the non-embedded SSI model, i.e. in the Y-direction for the embedded SSI model, incoherent response becomes larger than coherent response in the 12-14 frequency band.

- The motion incoherency effects are larger for higher frequency ranges. The magnitudes of the ISRS reductions depend significantly on soil site conditions. For the hard-rock site, the motion incoherency effects reduce the SSI response for all frequency ranges, but more drastically in the high-frequency range above 10-12 Hz. For the soft-soil condition, the motion incoherency effects manifest significantly starting at lower frequency ranges, well below 10 Hz when the soft soil coherence function is used.

From the above remarks, it is clear that the combined effects of embedment and motion incoherency are much more complex and less intuitive for soil sites. Therefore, it appears that considering the combined effects of embedment and motion incoherency soil sites is important. For hard-rock sites the motion incoherency effects for the embedded model can be scaled from the non-embedded model results.

It should be noted that for the incoherent SSI analyses shown herein we used the same coherency function for non-embedded and embedded structures. No slight upper adjustment of coherency function was made for embedded structures founded on soil sites as suggested by Abrahamson (2007). This aspect is currently under investigation.

It should be noted that the 2007 Abrahamson soil coherence function is currently not accepted by US NRC. Only the 2007 Abrahamson hard-rock coherence function is permitted by US NRC at this time.

5 CONCLUSIONS

Based on the investigated case studies shown in this paper, the following conclusions are drawn:

1) The effects of motion incoherency are similar for non-embedded and embedded nuclear structures. The SSI results shown herein indicate that motion incoherency effects are significant for both rock and soil sites. Typically, motion incoherency effects are larger for rock sites in high frequency range.

2) Combined effects of embedment and motion incoherency are much more complex for soil sites than for rock sites. For rock sites, it appears that motion incoherency effects are to reduce the SSI response at all frequencies, but more drastically in the high frequency range, above 10-12 Hz. For soil sites, the motion incoherency effects manifest visible at much lower frequencies, below 10Hz, where global, dominant structural vibration modes exist.
3) For structures with significant mass eccentricities, motion incoherency effects could amplify the torsional SSI responses, as shown herein for the AP1000-based stick model on a soil site, in Y direction.

As practical recommendations, we believe that for soil sites, the combined effects of motion incoherency and embedment have to be considered. For hard-rock sites, since motion incoherency effects have similar trends for non-embedded and embedded SSI models, the use of simple reduction factors might be acceptable.

We believe that more study is worthwhile to propose and gain acceptance for the use of soil coherence function by the US NRC.

REFERENCES

Abrahamson, N. (2005). Spatial Coherency for Soil-Structure Interaction, Electric Power Research Institute, Technical Update Report 1012968, Palo Alto, CA. December.

Abrahamson, N. (2006). Program on Technology Innovation: Spatial Coherency for Soil-Structure Interaction, Electric Power Research Institute, Palo Alto, CA, and US Department of Energy, Germantown, MD, Report 1014101, December.

Abrahamson, N. 2007. Effects of Seismic Motion Incoherency Effects EPRI Palo Alto, CA, TR-1015111

Ghiocel, D.M. 2007. Stochastic and Deterministic Approaches for Incoherent Seismic SSI Analysis as Implemented in ACS SASSI, Appendix C, Electric Power Research Institute, Palo Alto, CA and US Department of Energy, Germantown, MD, EPRI Report TR-1015110, November

Ghiocel, D.M. 2009. ACS SASSI NQA Version 2.3.0, User Manuals, Technical Reports, GP Technologies, Inc., Rochester, NY

Johnson, J.J., Short, S.A., and Hardy, G.S. (2007). Modeling Seismic Incoherence Effects on NPP Structures: Unifying CLASSI and SASSI Approaches, Paper K05/5, SMiRT 19, Toronto, Canada, August 12-17, 2007.

Short, S.A., G.S. Hardy, K.L. Merz, and J.J. Johnson (2006). Program on Technology Innovation: Effect of Seismic Wave Incoherence on Foundation and Building Response, Electric Power Research Institute, Palo Alto, CA and US Department of Energy, Germantown, MD, Report No. EPRI TR-1013504, December.

Short, S.A., G.S. Hardy, K.L. Merz, and J.J. Johnson. 2007. Validation of CLASSI and SASSI to Treat Seismic Wave Incoherence in SSI Analysis of NPP Structures, Electric Power Research Institute, Palo Alto, CA and US Department of Energy, Germantown, MD, EPRI Report TR-1015110, November

