Seismic Motion Incoherency Effects for Nuclear Complex Structures On Different Soil Site Conditions

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ABSTRACT
The paper presents results obtained from a sequence of research case SSI studies. The paper focuses on the effects of incoherency on the seismic SSI response of nuclear complex islands and structures with surface and embedded foundations, for rock and soil sites. These case studies include the EPRI AP1000 NI complex stick model [1] with and without embedment, a generic large-size shear wall structure with surface foundation, and a generic deeply embedded concrete pool structure. In addition to motion incoherency effects we also looked at wave passage effects for the large-size nuclear structure. The incoherent versus coherent SSI results are compared in terms of acceleration in-structure response spectra (ISRS) and structural forces and moments in the structural elements.

SEISMIC MOTION INCOHERENCY

Seismic motion incoherency is due to local spatial random variations of seismic ground motion in a 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 [2]. 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 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 coherence functions for soil conditions [2]. The coherence function is unity for coherent SSI analysis. The coherence function amplitude is near unity at low frequencies and reduces with frequency and separation distance between the observation points in the free-field.

The methodology used for incoherent SSI analysis is based on the Stochastic Simulation approach. The incoherent SSI methodology used is based on the Stochastic Simulation approach implemented in the ACS SASSI code [3] that was validated by EPRI [1] and endorsed by US NRC [6]. The Stochastic Simulation approach (called SASSI-Simulation in the EPRI studies) is similar to the Monte Carlo simulation used for probabilistic analyses. The theoretical basis of the Stochastic Simulation approach is described elsewhere [1, 4]. The (mean) incoherent SSI response is computed as the average of the results computed from a set of statistical SSI analyses using random field realizations of the incoherent free-field motion input. Besides the mean incoherent SSI responses, the SSI the Stochastic Simulation approach could provide insightful information on the scatter of the SSI responses that can be useful for both design and probabilistic risk assessment studies.

For incoherent SSI analyses, a set of 10 stochastic simulations were used to compute the mean incoherent ISRS. As shown in the EPRI validation studies [1] a reduced number of simulations, as low as 5 simulations, are sufficient to get reasonably accurate mean incoherent ISRS estimates. It was considered that the use of a set of 10 simulations is consistent with the EPRI recommendations, and is sufficient for accurately predicting mean incoherent ISRS.

CASE STUDIES

Three case studies are considered herein: i) the EPRI AP1000 NI complex stick model [1] with and without embedment, ii) a generic large-size shear wall structure with surface foundation and iii) a generic deeply embedded concrete pool structure (UHS type). The SSI models for the three case studies are shown in Figure 1.

AP1000 NI Stick Model

Before starting the parametric SSI studies, the AP1000 stick model foundation size was modified from the 150ft x 150ft size used in the EPRI studies [1] to the 158ft x 254ft size that is closer to the actual sizes of the AP1000 NI complex (Figure 1a). The EPRI soil layering has a shear wave velocity, Vs varying from 3,500 fps at ground surface to 11,000 fps in the depth. An additional hard-rock (HR) site condition with uniform Vs of 8,000 fps was also considered. The 2007 Abrahamson hard-rock coherency function [2] was used for both site conditions. Seismic input was defined by a site-specific UHRS high-frequency input, the same used in EPRI benchmark studies [1].

Figure 2 compares the 5% damping ISRS at the AP1000 NI basemat center for the two site conditions and foundation sizes, EPRI soil [1] with a foundation of 150ft x 150ft and hard-rock site with a foundation of 158ft x 254ft. It should be noted the incoherency effects are significantly larger for the hard-rock site and the larger foundation size. Also note that the soil stiffness plays a key role on the incoherency effects. The higher the frequency content of the basemat motion is, the larger incoherency effects are. For EPRI soil, the dominant ISRS are in 8-12 Hz range for the horizontal direction and about 15 Hz for the vertical direction, while for hard-rock site the dominant ISRS peak is 30-40 Hz in both the horizontal and vertical directions.

For the modified AP1000 stick model with a larger foundation size, the seismic input and soil layering were changed to reflect two different soil site conditions and two different foundation embedment conditions. The modified AP1000 stick model was considered with no embedment, as in EPRI study, and with 40 ft embedment, respectively. The control motion was defined at the ground surface.

For soil sites, seismic input was defined by the RG 1.60 input applied in conjunction with the 2007 Abrahamson soil coherency function [2]. Soil layering was assumed to be a uniform deposit with Vs of 1000 fps. For rock sites, seismic input was defined by a site-specific, hard-rock high-frequency (HRHF) input applied in conjunction with the 2007 Abrahamson hard-rock coherency function [2]. The HRHF input was the same with the site-specific UHRS type input used in EPRI study [1]. Soil layering was assumed to be a uniform deposit with Vs of 8,000 fps. Figure 3 shows the 2007 Abrahamson plane-wave coherence functions that were used.

Figures 4 through 7 show the coherent and incoherent ISRS computed for the surface and embedded AP1000 NI stick model on the rock and soil sites. The 5% damping ISRS are computed at basemat center and top of SCV in Y and Z directions. Figures 4 and 5 are for the rock site and Figure 6 and 7 for the soil site.

Overall, it should be noted that ISRS computed for the rock site indicates much larger incoherency effects that manifest by reducing largely the ISRS amplitudes in high-frequency range. This is due to the fact that the ISRS computed for rock sites have much larger high-frequency content than ISRS computed for soil sites. Also, the incoherency effects appear to be larger for vertical ISRS, since vertical ISRS have usually higher frequency content than horizontal ISRS.

Figures 4 through 7 show that the embedded sites have similar reductions in ISRS as surface founded sites. ISRS for embedded sites are lower than ISRS for surface founded sites for both coherent and incoherent motions. Embedment effects manifest more pronounced in the mid-frequency range rather than in the high-frequency range.

Figure 8 shows the coherent and incoherent shear forces in the AP1000 NI structures, ASB, CIS and SCV (see [1] for model details) computed for the soil site condition. It should be noted that the effects of embedment and incoherency slightly decrease the structural shear forces by 10-30%.

Before we discuss other investigated case studies, we would like to make some comments on a very important SSI analysis implementation aspect of the SASSI-based methodology. Figure 9 compares results obtained using the Flexible Volume (FV) and Subtraction/Flexible Interface (FI) methods [3, 5]. The Subtraction/FI method is applied as recommended in the technical literature by original implementers using the basement-soil interface nodes as SSI nodes. An alternative to the Subtraction/FI method is using all the excavation volume boundary nodes as SSI nodes, including the excavation volume top nodes at the ground surface. The application of Subtraction/FI with all boundary excavation volume including top nodes is marked in the legends of the ISRS plots by FIT.

To check the robustness of FI method, a coarse horizontal excavation volume mesh of 20ft x 10 ft was used. Figure 9 left ISRS plots show that for this coarse mesh, the FI is unstable and produces a large ISRS peak at about 18 Hz for both the coherent and incoherent ISRS. However, if we include the ground surface excavation volume nodes as SSI nodes, then, the FI method denoted by FIT in legend becomes much more robust and provides ISRS accurate results close to the reference FV method, as shown in Figure 9 right ISRS plots.

<u>Large-Size Shear Wall Structure</u>

The large-size shear wall structure is a generic modular configuration building with a horizontal foundation size of 450ft x 350ft (Figure 1b). The shear wall structure was assumed to be founded on a rock site with Vs of 4,500 fps. The seismic input was defined by the HRHF input used also to the AP1000 stick model. The 2007 Abrahamson hard-rock coherency model was used. For this large-size structure we also considered the wave passage effects. Since we assumed that the soil deposit has a soil layering inclination in a direction that makes about 30 degree with longitudinal axis of the foundation, we considered a horizontal apparent wave speed of 6,000 fps in a 30 degree oblique direction. The 6,000 fps is an extreme low apparent speed that was considered to produce an upper bound of the wave passage effects.

Figure 10 shows the instantaneous SSI acceleration distributions in the basemat at arbitrary time by the deformed shape of the base slab. The base slab was isolated from the rest of the structure. The base slab deformed plots were computed for the coherent input (a), incoherent input (b, left) and incoherent plus wave passage input (b, right). It should be noted that for the large-size and flexible basemat, the effects of incoherency appear to be important. Based on the Figure 10 plots, it is expected that the base slab maximum bending moments increase due to incoherency and wave passage. It is clear from Figure 10 that traditional coherent analysis that assumes that the entire 450 ft x 350 ft soil area under the foundation moves as a "rigid body" is unrealistic and against recorded evidence in seismographic dense arrays. This "rigid body" assumption for soil motion could under significantly evaluate the bending of the base slab. We noticed that incoherency and wave passage effects could increase the base slab bending moments by 50%, or even more (not shown herein).

Table 1 shows the effects of incoherency and wave passage on the forces and moments in the external transverse shear wall. Table 1 shows that incoherency could increase the out-of plane bending moments in shear wall by 10% if no wave passage is considered (Va = infinity), and by 30% if passage is included (Va = 6,000). The axial and shear forces could increase by 10-15% if incoherency and wave passage are included. More research is needed to quantify for practice these qualitative aspects.

<u>Deeply Embedded Concrete Pool Structure</u>

The concrete pool structure is shown in Figure 1c. The foundation size in horizontal plane is 80ft x 50 ft. The embedment is 30 ft. The pool structure is a very flexible structure since is an open box structure. The perimeter wall thinckness is 3 ft. The soil deposit is a viscous elastic half-space with Vs of 1,000 fps. Seismic input was defined by a RG 1.60 input ar ground surface. The 2007 Abrahamson soil coherency function was used for incoherent SSI analyses.

Figure 11 shows the coherent and incoherent structural acceleration deformed shapes at an arbitrary time. It should be noted the structural deformation patterns show that for incoherent inputs in addition to regular mode of vibration patterns there are present random patterns due to presence of short wave length random components. Thus, the differential soil motions due to incoherency create local differential soil pressures that affect the vibration shape of the concrete structure.

Figure 12 shows the membrane stresses in the 30 ft embedded concrete pool structure. It is obvious that the incoherent stresses are much lower on the top of the pool structure due to reduced inertial forces at the top due to incoherency. However, at lower levels under the ground surface, the incoherent, random short wavelength components could produce locally larger stresses in the concrete structure due to differential soil motions. It is believed that the wave scattering phenomenon is largely affected by incoherency due to the presence of non in phase components. More research is needed to quantify for practice these qualitative aspects.

CONCLUSIONS

The effects of motion incoherency:

1) Reduce the ISRS amplitudes in high–frequency range. For rock sites, large ISRS amplitude reductions of 2-3 times are possible.

2) Increase bending moments in basemats

3) For large foundation sizes, increase the shear wall forces in external walls

4) The inclusion of wave passage effects could be favorable for interior shear walls and detrimental for external walls located at the longitudinal edges. More in-depth research is needed.

5) Application of Subtraction/Flexible Interface method as recommended in the technical literature could provoke unstable SSI results, most often shown by unrealistically high ISRS peaks. The use of all excavation volume boundary nodes as SSI nodes, could provide a more stable and accurate SSI solution for Subtraction/Flexible Interface. However, the addition of the top, ground surface nodes, as SSI nodes impacts severely on the numerically efficiency of Subtraction/Flexible Interface.

6) For deeply embedded structures, the incoherency effects are to reduce the global resultant of the local soil pressures, but locally might produce "hot spot" pressures due to short wavelength soil motion components. Wave scattering effects around deeply embedded structures are sensitive to motion incoherency. More in-depth research is needed.

REFERENCES

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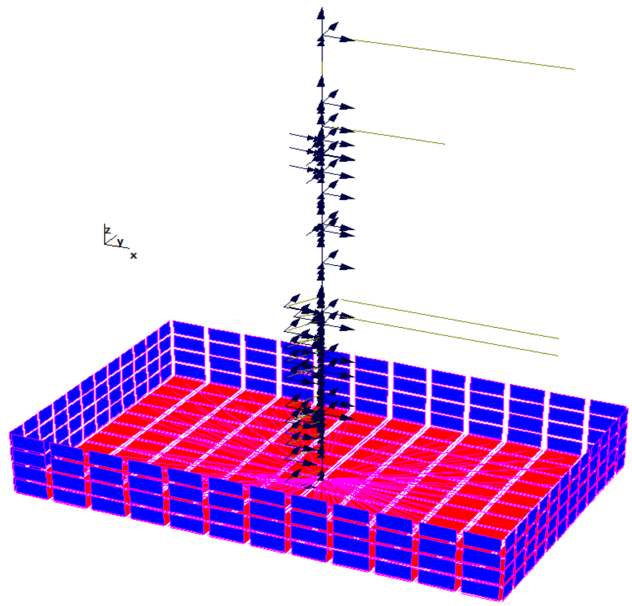
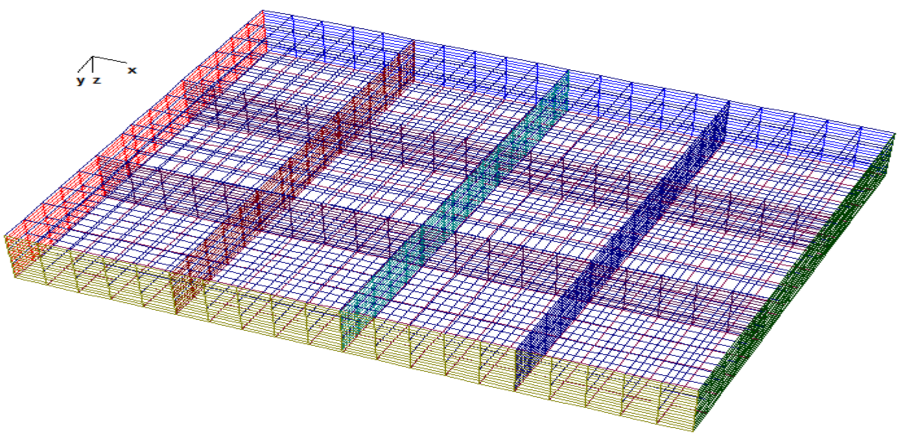
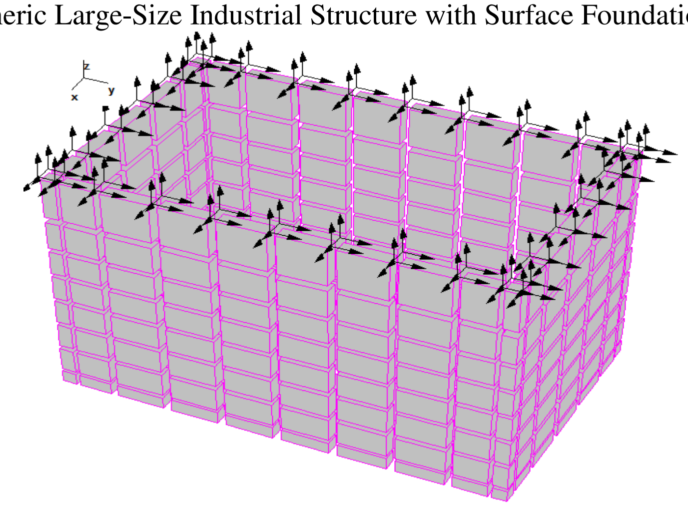
6. USNRC Final Interim Staff Guidance DC/COL-ISG-01 (2008) "Seismic Issues Associated with High Frequency Ground Motion"



a) EPRI AP1000 Stick Model with 40ft Embedment and Foundation Size of 158ft x 254ft



b) Generic Large-Size Industrial Structure with Surface Foundation of 450ftx350ft



c) Generic 30 ft Embedded Concrete Pool Structure with Foundation Size of 80ft x 50ft

Figure 1 Investigated SSI Models

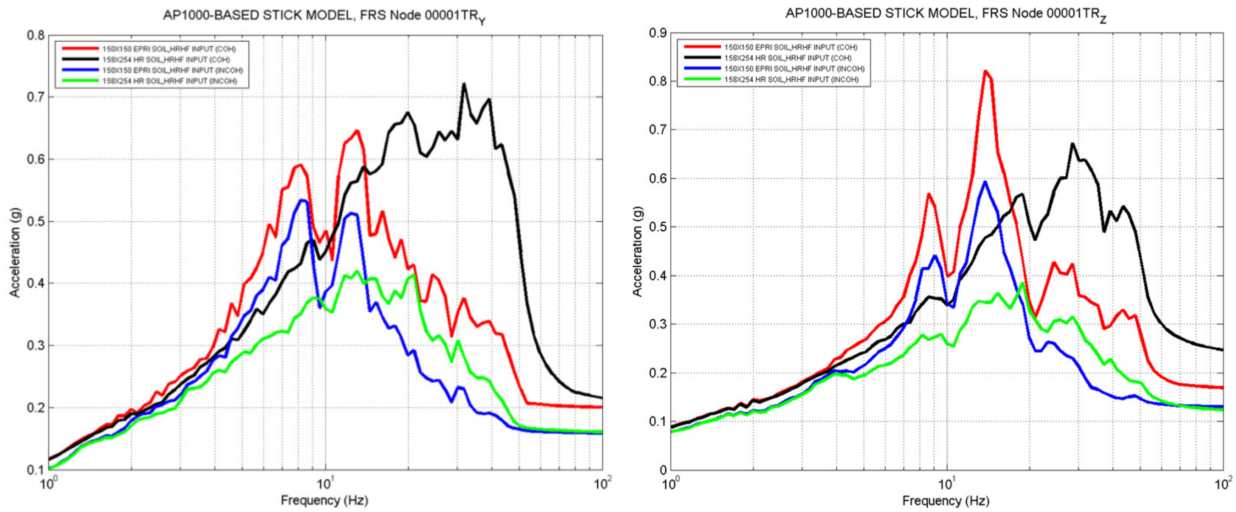


Figure 2 Effect of Foundation Size and Rock Site Condition on AP1000 Stick ISRS at Basemat Center

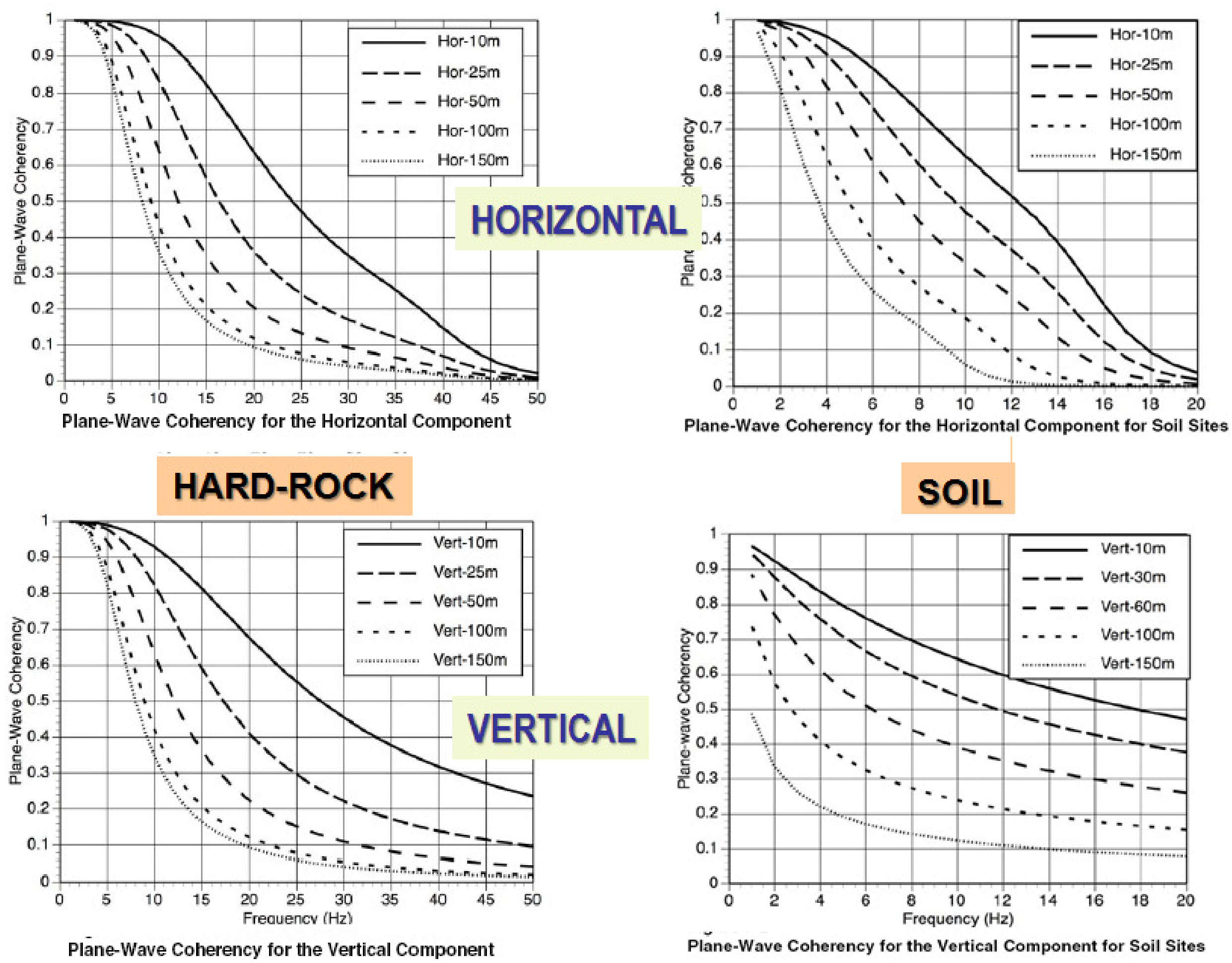


Figure 3 2007 Abrahamson Plane-Wave Coherency Models for Rock and Soil Site Conditions

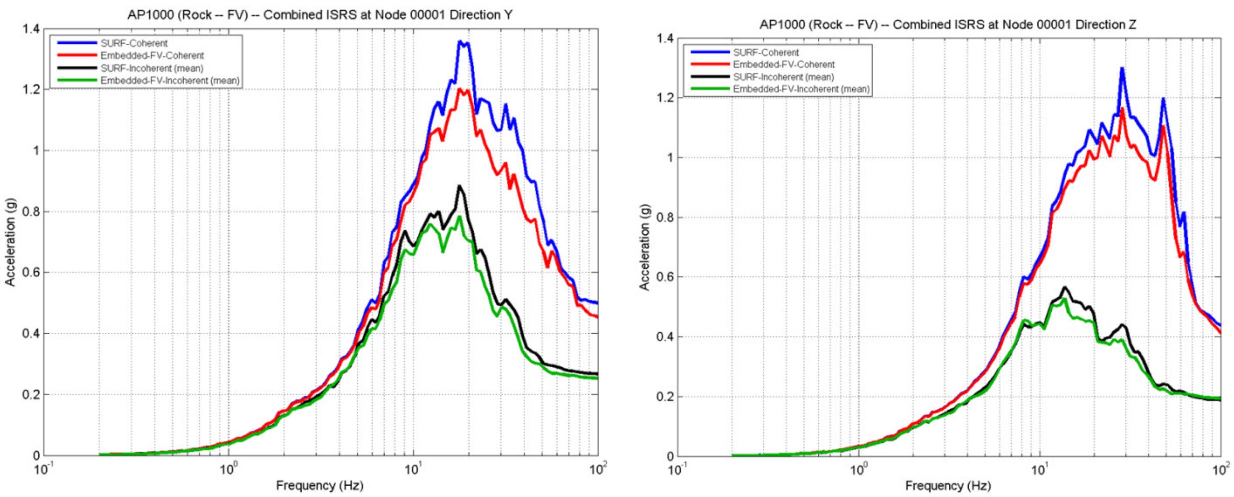


Figure 4 AP1000 Stick ISRS for Y (left) and Z (right) Directions at Basemat Center for Rock Site

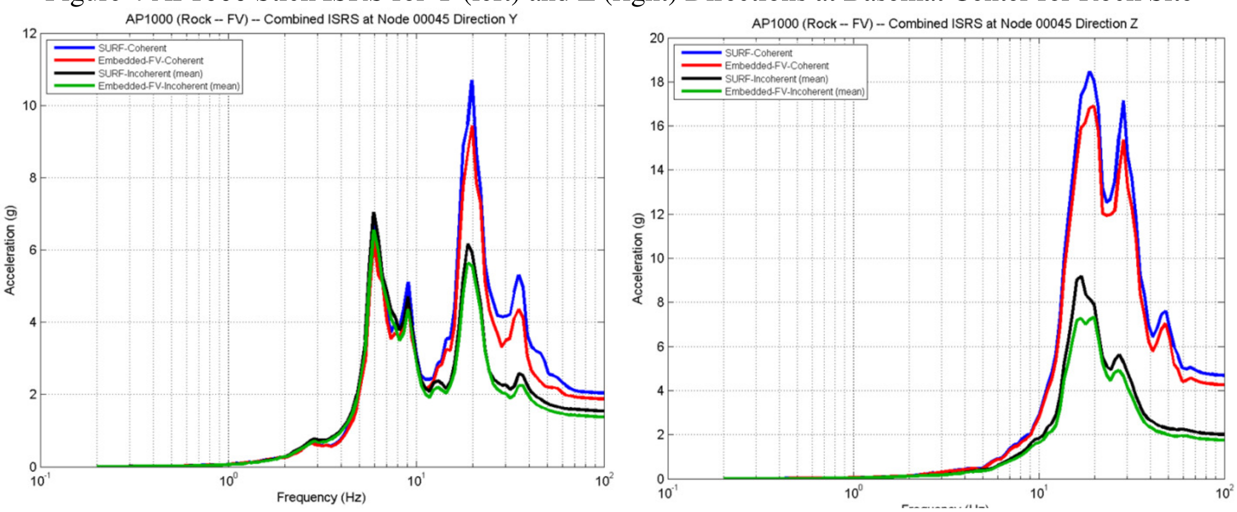


Figure 5 AP1000 Stick ISRS for Y (left) and Z (right) Directions at Top of SCV for Rock Site

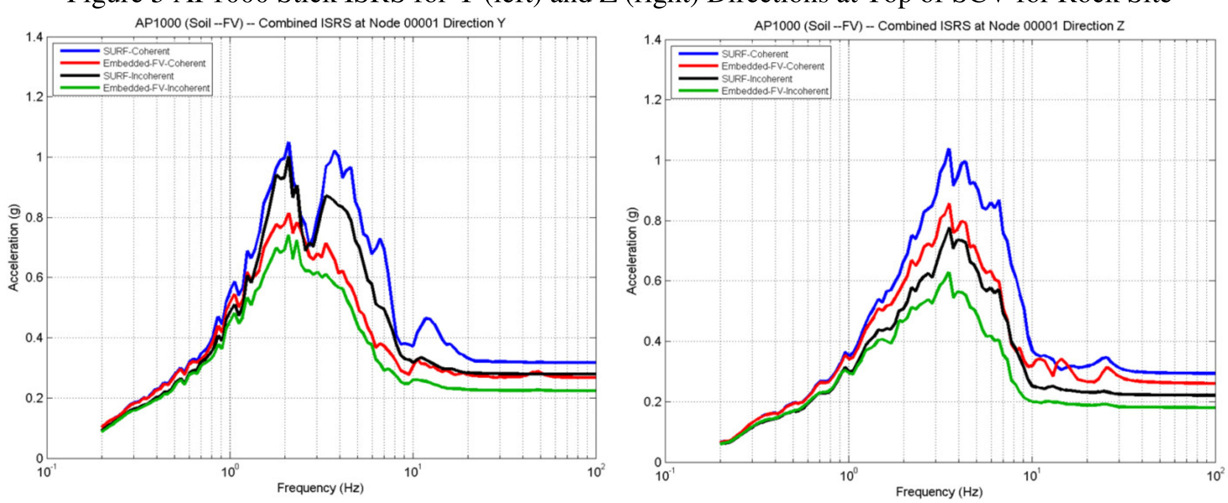


Figure 6 AP1000 Stick ISRS for Y (left) and Z (right) Directions at Basemat Center for Soil Site

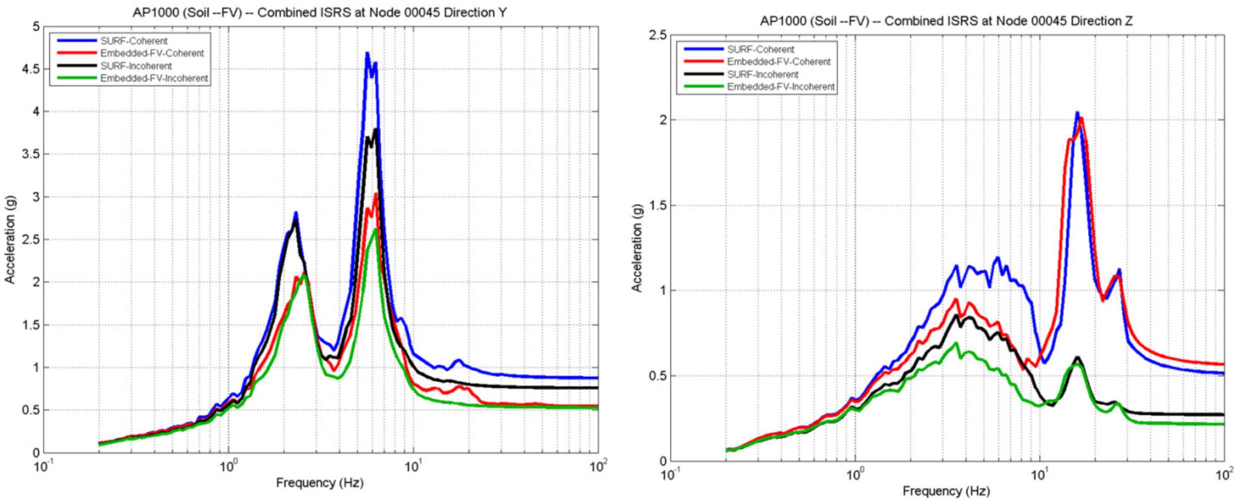


Figure 7 AP1000 Stick ISRS for Y (left) and Z (right) Directions at Top of SCV for Soil Site

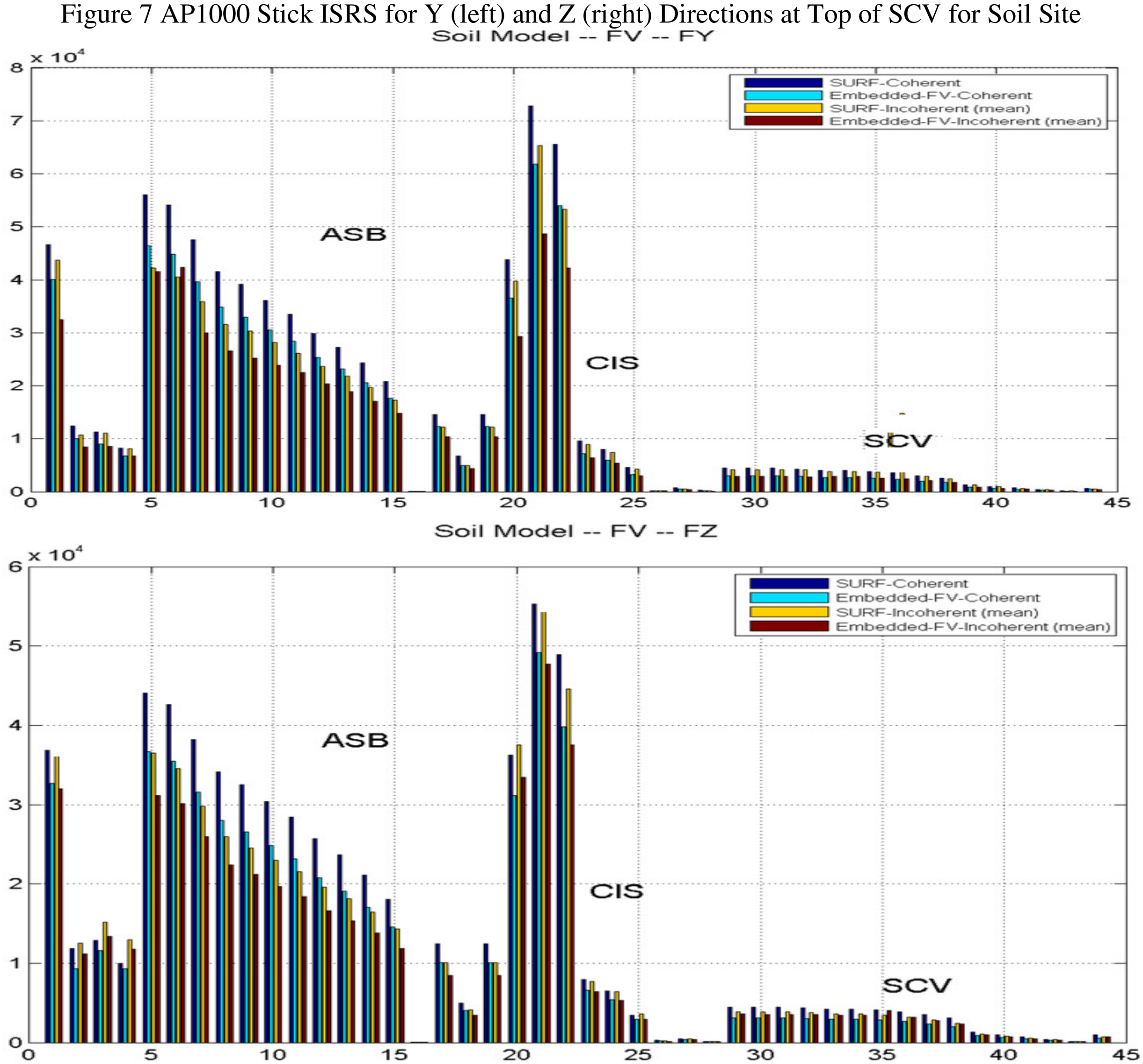


Figure 8 AP1000 Stick Shear Forces in X (upper) and Y (lower) Directions for Soil Site
(abscisa axis numbers show the stick element numbers for ASB, CIS and SCV sticks)

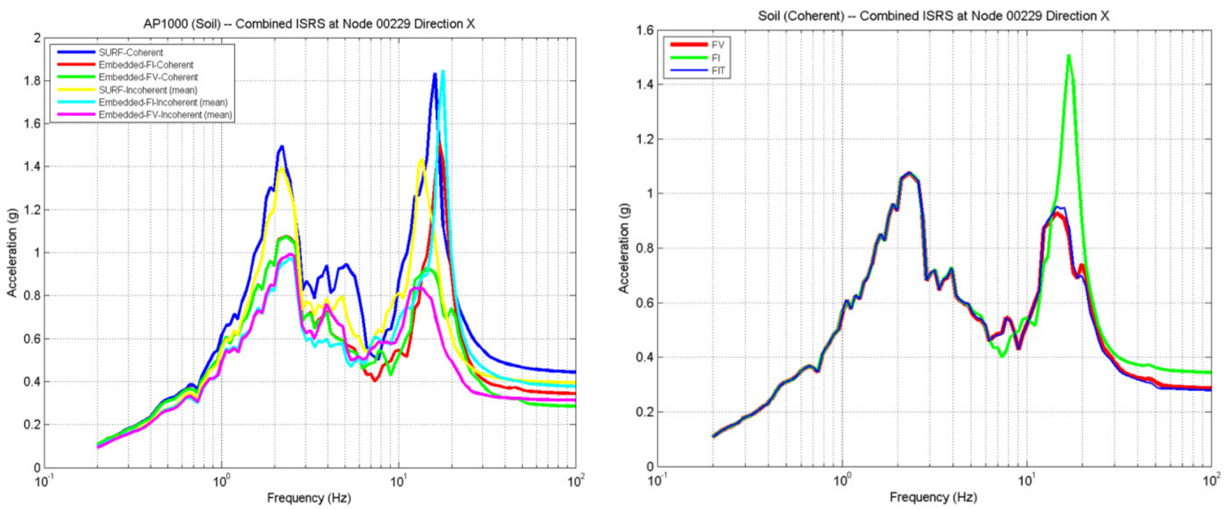
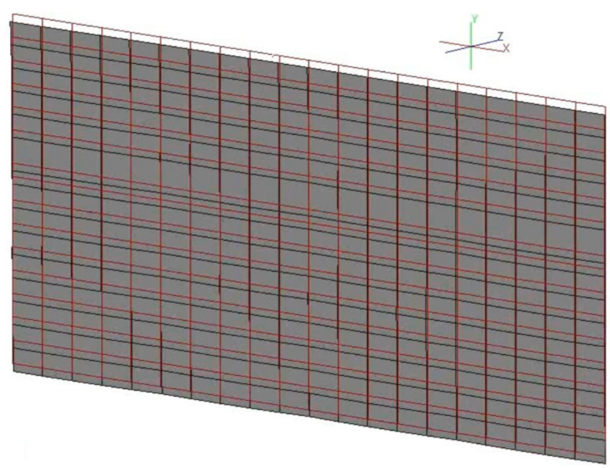
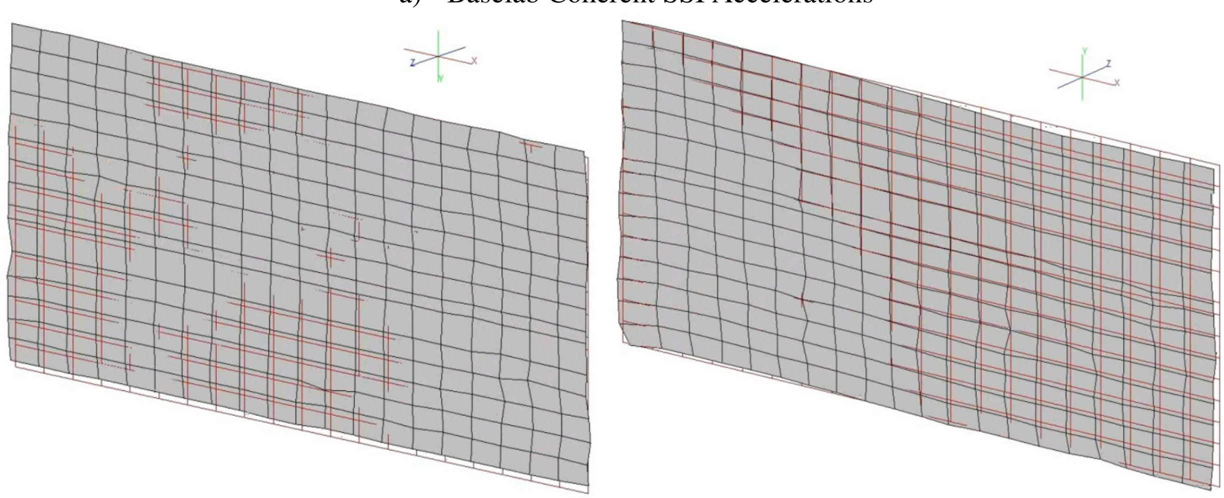


Figure 9 Comparative ISRS Computed at Top of CIS Using Flexible Volume (FV) and Subtraction (Flexible Interface, FI and FIT); Coherent and Incoherent ISRS Computed for Surface and Embedded Models Using FV and FI (left) and Coherent ISRS for Embedded Model Using FV, FI and FIT (right)



a) Baselab Coherent SSI Accelerations



b) Baselab Incoherent SSI Accelerations Without (left) and With Wave Passage (right)

Figure 10 Baselab SSI Acceleration Distribution Values at Arbitrary Time

Element	Analysis	Va	Value	Axial	Shear	Moment
	coh		max	35.398	28.541	3.476
			max	26.987	24.671	3.809
external wall	incoh	Infinity	ratio	0.762	0.864	1.096
			max	40.309	31.365	4.474
		6000	ratio	1.139	1.099	1.287
	coh		max	19.313	45.618	2.874
			max	14.940	35.326	2.242
interior wall	incoh	Infinity	ratio	0.774	0.774	0.780
			max	13.807	32.663	1.811
		6000	ratio	0.715	0.716	0.630

Tabel 1 Comparison of Coherent and Incoherent Shell Element In-Plane Forces and Out-of-Plane Bending Moments

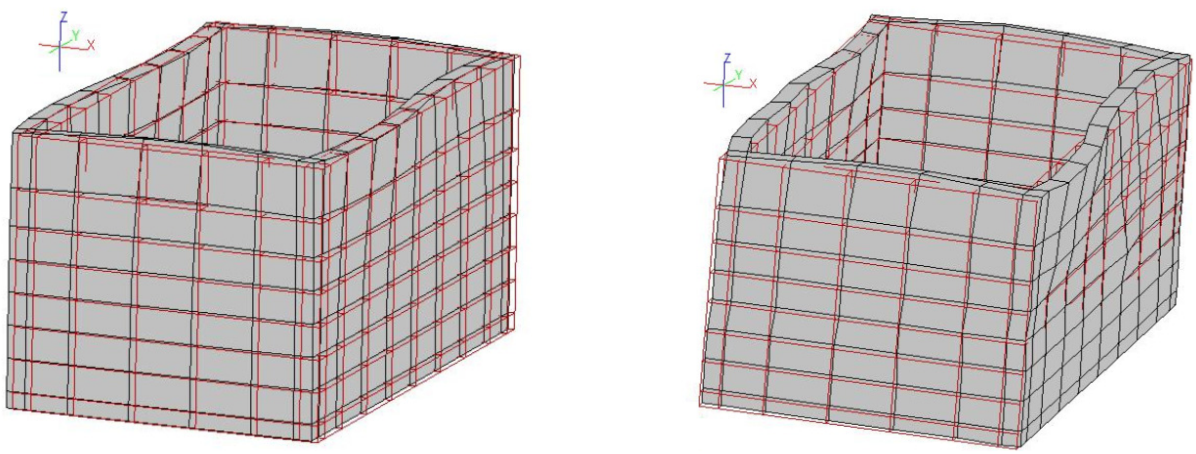


Figure 11 SSI Accelerations at Arbitrary Time for Coherent (left) and Incoherent (right) Inputs

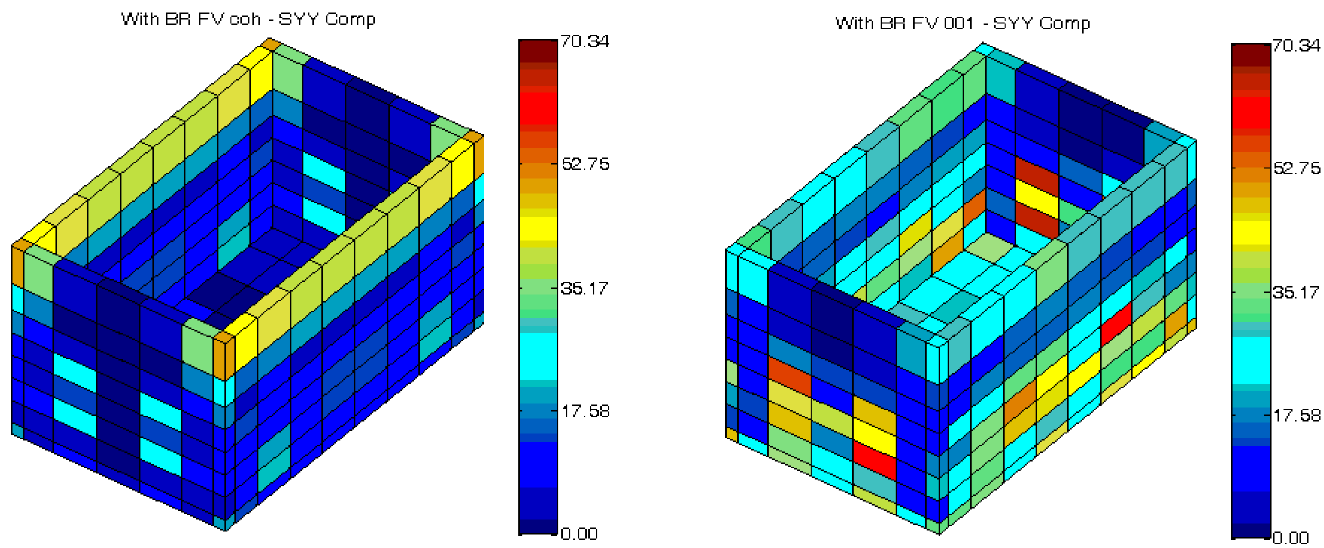


Figure 12 Coherent (left) and Incoherent (right) Membrane Forces in the 30 ft Embedded Concrete Structure Walls (embedment covers the lower 5 element layers)