Full Paper Transactions, SMiRT 28
Toronto, Canada, August 10-15, 2025

SEISMIC SSI ANALYSIS STUDY FOR DEEPLY EMBEDDED SMR STRUCTURES UNDER COHERENT AND INCOHERENT INPUTS

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ABSTRACT

The paper investigates the effects of the soil-structure interaction (SSI) for a typical deeply embedded Small Modular Reactor (SMR) structure subjected to coherent and incoherent ground motions. The paper investigation is a continuation of a previous research study of the authors (Ghiocel and Todorovski, 2022), which noted that the motion incoherency could affect seismic stress demands on the SMR embeddeed exterior walls. The incoherent motions produced by the soil deformation under non-vertically propagating waves can't be captured by the 1D wave propagation model used for the traditional SSI analyses with coherent input motions, especially for sites with nonuniform soil deposits. The kinematic SSI effects which are dominant for the response of the deeply embedded SMR may be amplified due to the motion incoherency affecting the distribution of seismic design demands on the SMR structure. To investigate these motion incoherency effects, a set of ACS SASSI analyses were perfromed on three different soil profiles representing: an uniform soil site; a deep soil site; and a shallow rock site. To also evaluate the effects of modeling of the conditions at the wall-soil interfaces, two models were used representing fully-bonded and smooth no-friction wall-soil interfaces. Evaluations of the soil-wall interface condtions on the SMR sesismic response were perfromed for both coherent and incoherent input motions. Discussion and recommendations for selection of low-frequency filters for incoherent SSI analysis are aslo presented.

CASE STUDY

Input motion incoherancy and soil-structure interface effects were evaluated for a reinforced concrete (RC) SMR structure with square footprint dimensions of 100 ft by 100 ft and a total height of 162.50 ft including 118 ft embedment. The SMR exterior and containment walls are 3 ft thick, while the interior compartment walls are 2 ft thick.

The SMR SSI model used for the study is described in Figures 1 and 2 and has a total of 30,924 nodes including 15,780 excavation nodes. The interaction nodes are plotted in Figure 2 with red dots and include 10 levels of interaction nodes out of the total of 30 levels of excavated volume nodes. The interface between SMR embedded wall and surrounding soil was assumed to be either a fully bonded or a smooth no-friction interface as described in Figure 2. The smooth interface was simulated by very soft, low stiffness tangential springs at the wall-soil interface. The bonded interface is modeled using both rigid tangential springs.

The right plot of Figure 3 shows the shear wave velocity profiles of the three generic site conditions investigated for this study, representing: (1) an uniform soil site with Vs = 1,500 fps; (2) a deep soil site (firm 270-60) with a gradual increasing stiffness from Vs of 500 fps to 5,000 fps at 700 ft depth; and (3) a shallow rock site (median 500-21) with a soil layer of about 80 ft depth and an average Vs of 1,000 fps resting above a baserock formation with average Vs of 6.500 fps. The 5% damped response spectra, shown in the left plot of Figure 3, define the amplitude and frequency content of the seismic motions at the ground surface used as input for this study.

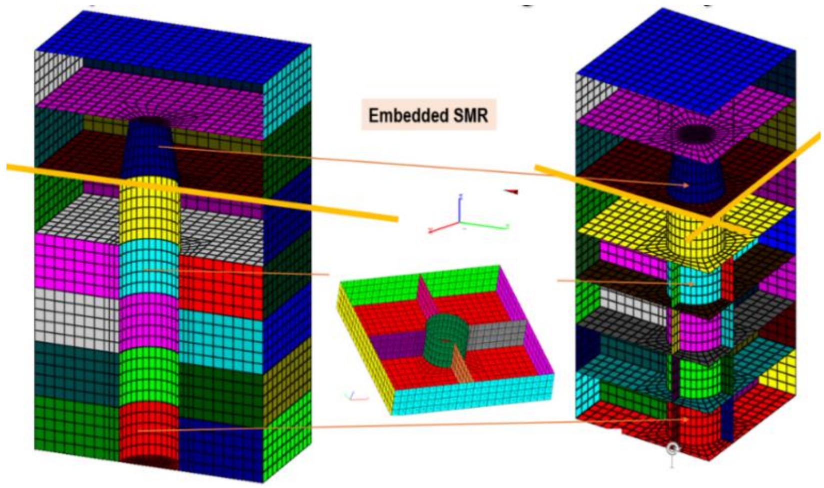


Figure 1 SMR Structure FE Model Description (left plots) including ISRS Output Locations (right plot)

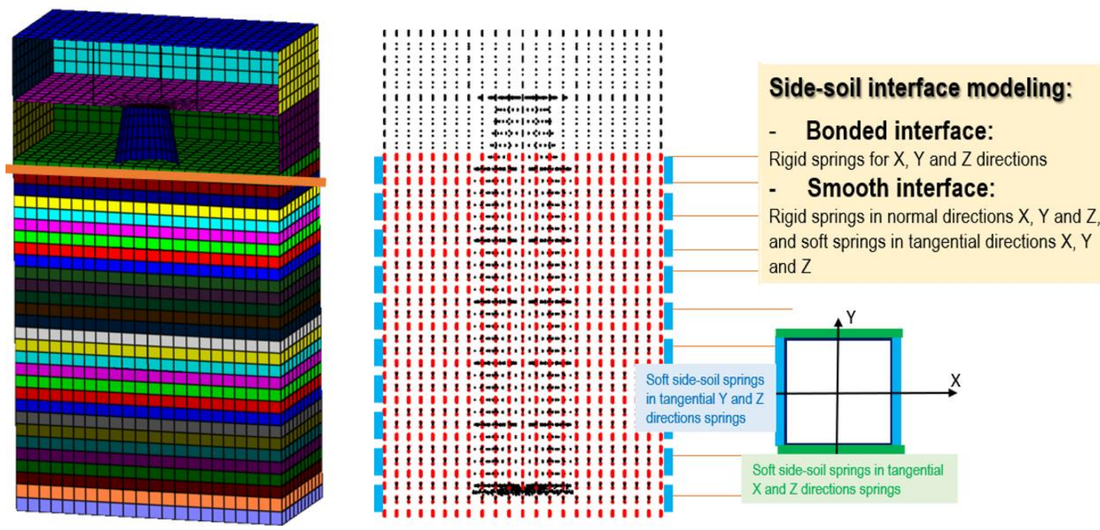


Figure 2 SMR SSI Model; FE Model Mesh (left), Nodes (middle) and Soil-Interface Modeling (right)

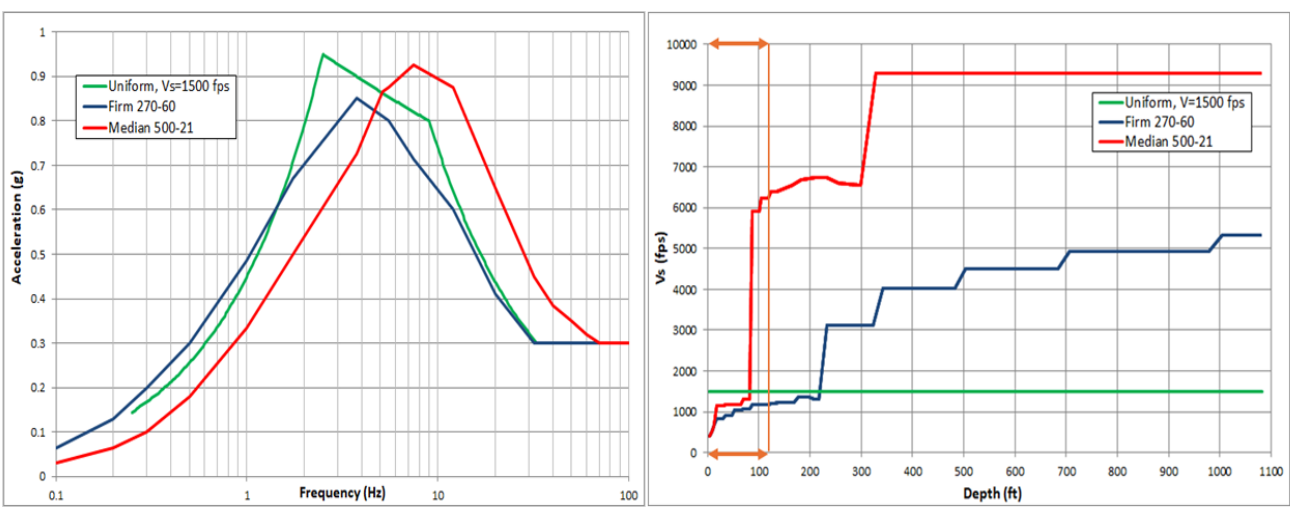


Figure 3. Site-Specific Site Conditions; Generic Response Spectra Scaled at 0.3g (left) and Shear Wave Velocity Profiles (right)

The US NRC Regulatory Guide (RG1.60) spectra defines the seismic input motion for the analysis of the uniformsoil site. The Firm and Median Generic Ground Motion Response spectra (GMRS) define the seismic input motions used for the analyses of the deep soil site (firm 270-60) and the shallow rock site (median 500-21), respectively. The input control motions for SSI analysis were defined at the SMR foundation level by in-column soil motions. The ground surface motions were scaled to peak ground acceleration of 0.6g for all SSI analyses. The Firm 270-60 and Median 500-21 generic design soil profiles together with the Firm and Median GMRS are obtained from the NEDO TLR 33914A (NEDO, 2022).

The incoherent SSI analyses were performed using the ACS SASSI NQA V4 sofware using the Stochastic Simulation (SS) approach that uses a rigorous Monte Carlo simulation for generating the sets of the seismic incoherent stochastic wavefields based on the Abrahamson coherency models. Ten sets of incoherent SSI simulations were considered to compute the incoherent responses as a mean of the ten simulations.

The seismic incoherent motion inputs were defined using the Abrahamson soil and rock coherence functions (Abrahamson, 2007). The soil coherence function was used for the incoherent SSI analyses of the uniform and the 270-60 soil profiles. The rock site coherence function was used for the analysis of the 500-21 shallow soil layer profile. The wave incoherency also included wave passage effects. The apparent traveling wave speeds were defined for soil and rock sites along a horizontal direction making an angle of 45 degrees with the two input directions. The alpha directionality factor of 0.50 corresponds to isotropic coherence functions, i.e. same coherence in all directions, as defined in the original Abrahamson incoherency models.

Figure 4 illustrates qualitative comparisons between the coherent (1D wave) and the incoherent (3D wave) seismic soil motions. Simulated incoherent motions are based on the dense array of recorded seismic waves including a random mix of inclined body and surface waves with different contributions defined by soil and rock coherency models in Abrahamson, 2007. These Abrahamson coherence functions are different for soil and rock sites indicating that the motion incoherency is much more pronounced for softer soil deposits than for harder soil and rock formations.

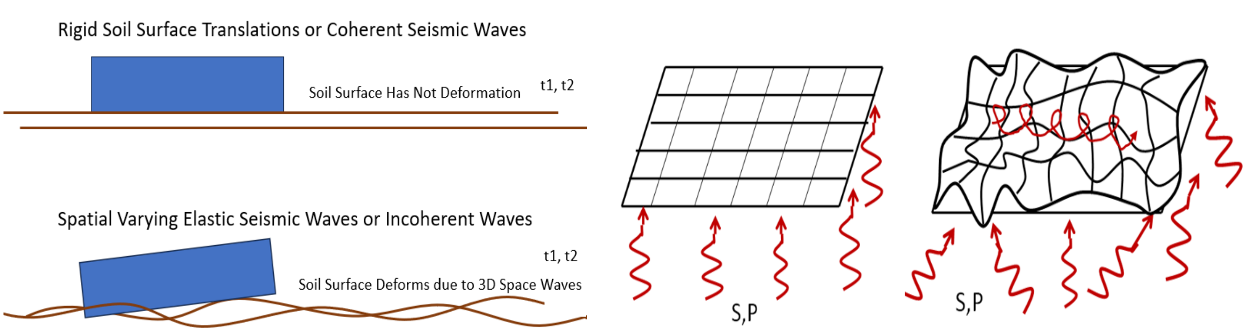


Figure 4 Qualitative Comparison Between Coherent and Incoherent Motion Inputs

The spatially varying motions are simulated based on dense array recorded motions and may include long-period displacement noise components which may affect the structural stress results by introducing artificial quasi-static forces in elastic foundation walls and basemats. Therefore, a Butterworth high-pass filter of order n = 5 with a corner frequency fc = 0.25 Hz was applied to the simulated wavefield motions to filter out the low frequency noise and ensure that the physical nature of the simulated motions is reasonably captured. Figure 6 shows the removal of low-frequency components for Butterworth filters of different orders n and a corner frequency fc = 0.25Hz (Falamarz-Sheikhabadi and Zerva, 2019).

Soil Profile	Wall-Soil Interface	Incoherent Parameter Inputs		
		Apparent Speed (fps)	Abrahamson Coherency Model	Alpha Directionality Factor
Uniform Soil: Vs=1500 fps	Rigid Springs	10000	Soil	0.5
	Soft Springs			
Nonuniform Soil: Firm 270-60	Rigid Springs			
	Soft Springs			
Nonuniform Soil: Median 500-21	Rigid Springs	1.00E+08	Rock	
	Soft Springs			

Figure 5 Coherence Model Input Parameters

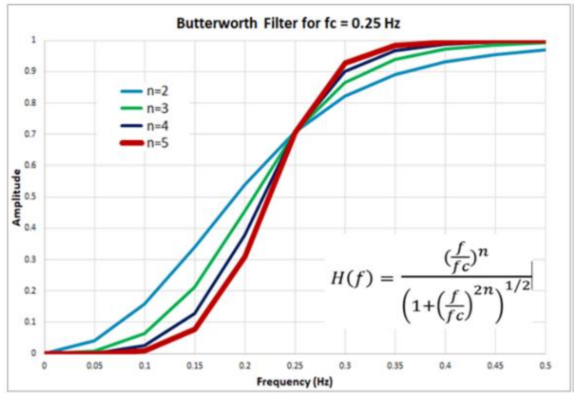


Figure 6 Butterworth Filter with fc =0.25 Hz

COMPARISONS OF SEISMIC SSI RESPONSES

The comparisons of results obtained from SSI analyses of the three soil profiles illustrate the significance of soil stiffness variations and seismic wave amplifications through the depth of embedment soil columns on the seismic response of the deeply embedded SMR. The left and right plot in Figure 7, respectively, depict accelerations of the SMR structure at one strong motion instance of time obtained from the SSI analyses of the 270-60 deep soil site and for the 500-21 shallow rock site. These two plots that use same plotting scale, indicate much higher contrast in the responses through the SMR embedment depth for the 500-21 shallow rock site (right) than for the more uniform 270-60 deep soil site (left). Amplified responses of the SMR can be observed at shallow depths below the ground surface that are driven by the response of the shallow top layer of soft soil in the 500-21 shallow rock profile.

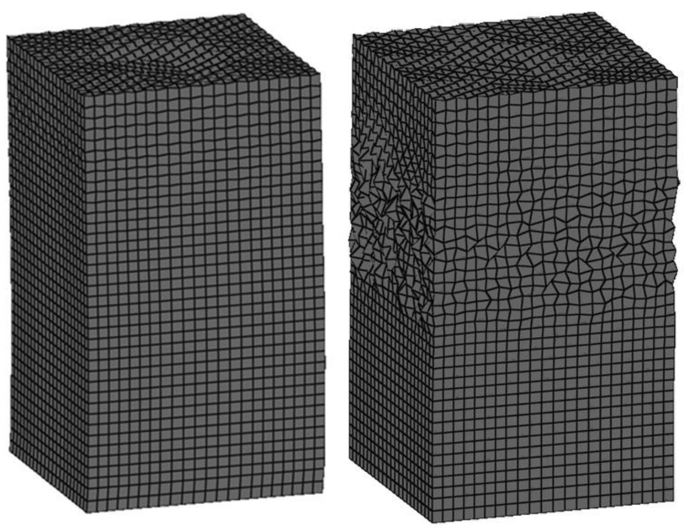


Figure 7 SMR Responses for 270-60 (left) and 500-21(right) Sites

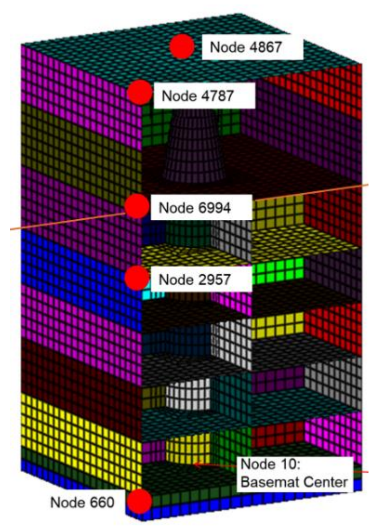


Figure 8 ISRS Output Locations

The 5% damped in-structure response spectra (ISRS) were compared for the the response at key SMR locations shown in Figure 8. Figures 9 and 10 compare the ISRS for the response at the SMR corner location at the ground surface level (Node 6994) obtained from the coherent and incoherent SSI analyses of all three soil profiles.

The comparisons in Figure 9 of horizontal ISRS obtained from analyses of models with smooth no-friction wall-soil interfaces (the left plot) and bonded wall-soil interfaces (the right plot) illustrates the importance of the modeling of the soil interface conditions on the computed SMR responses.

The comparisons of ISRS results from the analyses of the uniform and the (270-60) deep soil sites indicates that smoother interface conditions can amplify the sesimic response of the SMR when embedded in relatively unifrom soil.   resulting in significantly larger ISRS amplitudes. In contrast, the 500-21 shallow rock site analyses with the fully bonded SSI interface model produced larger ISRS amplitudes by up to 100%. The comparisons of ISRS obtained from the coherent and the incoherent analyses show that the input motion incoherency only slightlly lower the in-structure response of the deeply embedded SMR. The incoherency effects are not significant due to the small SMR foot-print dimensions.

As illustrated by the comparisons of the vertical ISRS results in Figure 10, trends in SMR in-structure response in the vertical direction are similar to those in the horizontal directions.

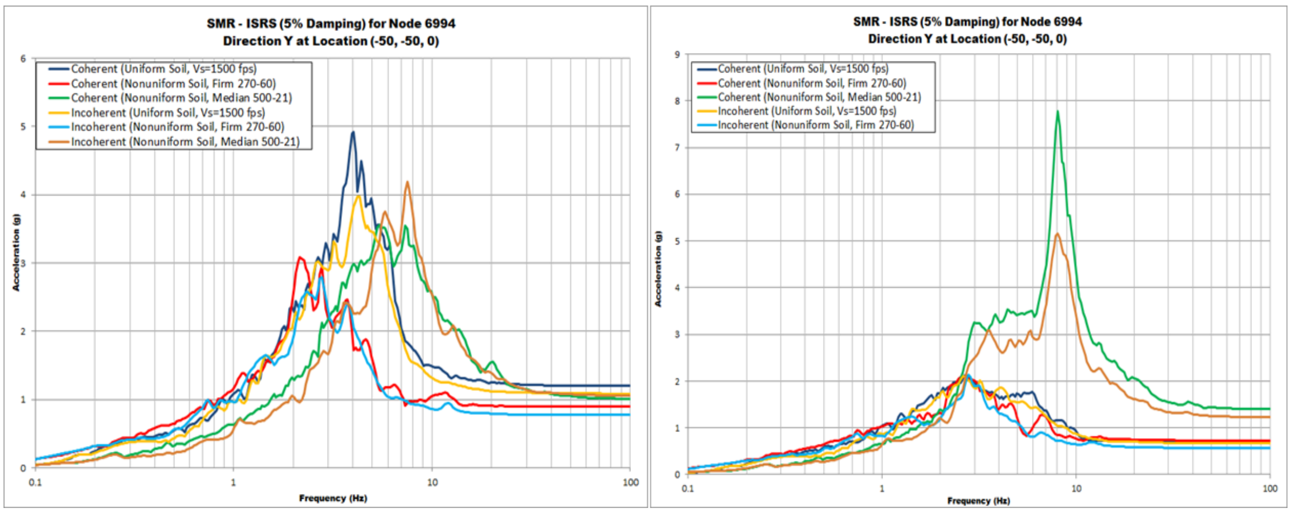


Figure 9 SMR Corner Y-Dir ISRS at Ground Surface for Smooth (left) and Bonded (right) Soil Interface

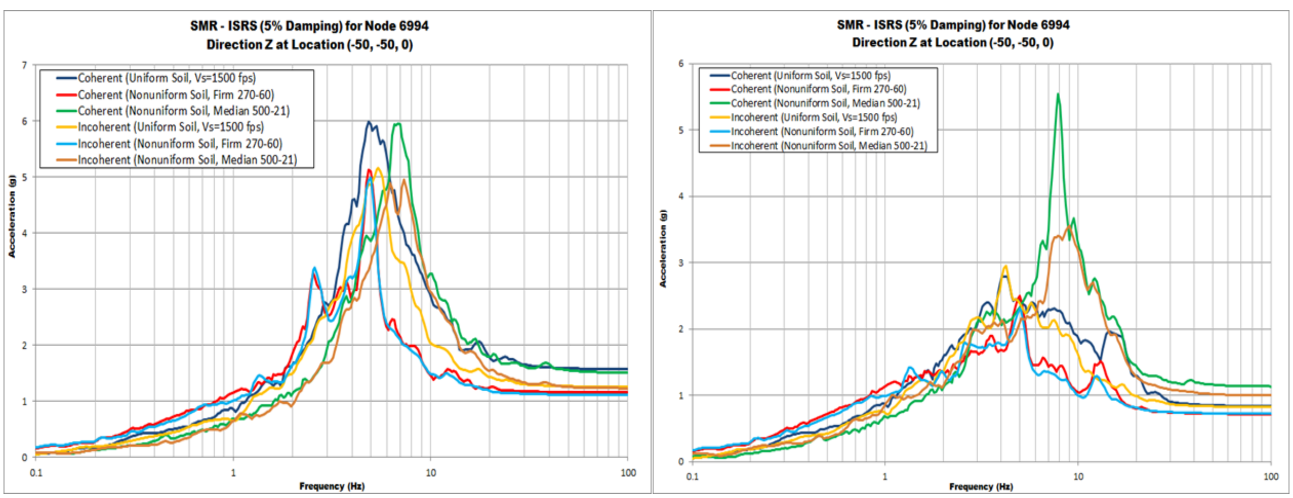
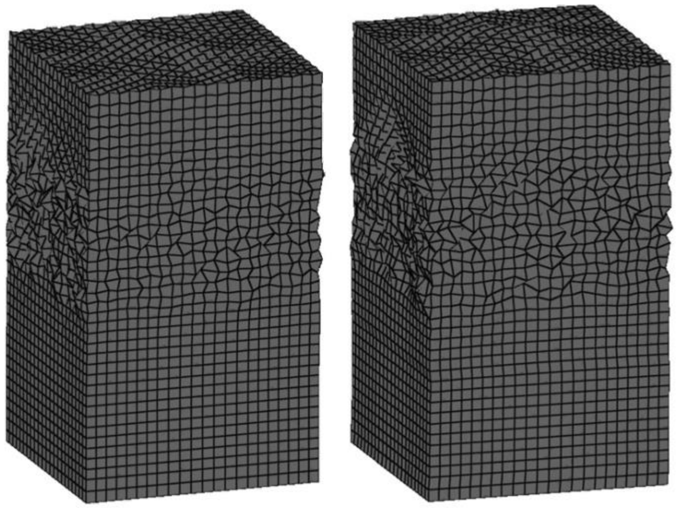


Figure 10 SMR Corner Z-Dir ISRS at Ground Surface for Smooth (left) and Bonded (right) Soil Interface

The two plots in Figure 11 show the distribution of nodal accelelration responses of the deeeply embedded SMR at the 500-21 shallow rock site at one instance of time of strong ground motion under coherent and incoherent input motions. The comparisons of the plots in Figure 11 illustrates that the incoherent motion apparently affects slightly larger the distribution of the acceleration response of the portion of the SMR wall that is embedded in the shallow layer of soft soil.



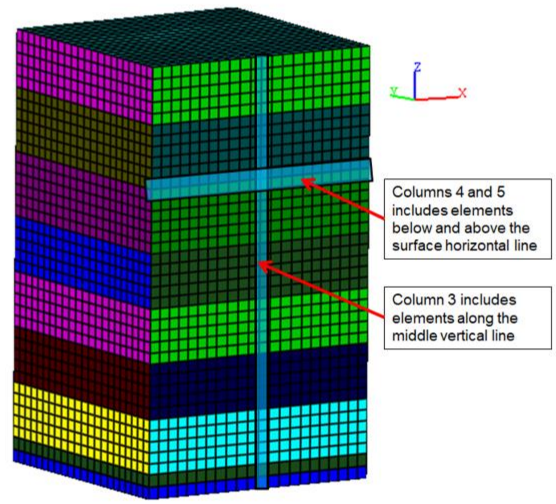


Figure 11 Coherent (left) vs. Incoherent (right) Responses for 500-21Shallow Rock Site

Figure 12 Selected Shell Element Groups

To illustrate how different site conditions, soil-wall interface conditions and ground motion incohernacy can affect the sesimic structural demands, the plots in Figures 13 through 17 present comparisons of results of SSI analyses of the three site profiles for the shell element in-plane shear forces (NXY), vertical membrane forces (NYY) and horizontal and vertical bending moments (MXX and MYY). These element stress results are presented for selected groups of shell elements of the SMR exterior wall depicted in Figure 12. Column 3 includes a vertical line of shells in the middle of the SMR wall from elevations roof elevation of 42 ft to basemat elevation of -116 ft. Columns 4 and 5 include two horizontal lines of shell elements located above and below ground surface elevations, respectively, that span from the left to the right edge.

Figures 13 and 14, respectively, show results for the Column 5 horizontal layer of wall elements for NXY shear forces and MYY bending moments, respectively, obtained from the SSI analyses with coherent input motionsin. Two plots are presented in these figure each showing results obtained from the analyses of the three site profiles. The plots on the left present results from SSI analyses of the model with no-friction soil-wall interfaces, while on the right are the plots presenting results from the SSI model with fully bonded wall-soil interface conditions. The comparisons of element stress results show significantly lower wall internal force and moment demands when the SMR is located at the 270-60 deep softer soil site than for the uniform stiffer soil site with Vs = 1,500 fps and the 500-21shallow rock profile. The largest wall forces and moment demands are observed in the portion of the SMR wall embedded in the top shallow layer of soft soil obtained from the 500-21 shallow rock site analysis of the model. with fully bonded wall-soil interfaces. Maximum wall forces and moments are obtained considering fully bounded conditions at the wall soil-interfaces that are 3-4 times larger than those calculated using smooth no-friction interface conditions.

Figures 15, 16 and 17 present results of coherent and incoherent SSI analyses of the model representing no friction resistance at the soil-wall interfaces for NYY forces and MXX moments in the Column 5 vertical line of shell elements. Each figure compares the element stress results for one of the three sites considered. The comparisons of the results in Figure 15 shows that the effects of ground motion incoherency are very small for the uniform soil profile (Vs=1,500 fps). The results in Figures 16 and 17 indicate more pronounced ground motion incoherency effects for the 270-60 deep soil and the 500-21 shallow soil layer sites The results obtained from analyses of the model assuming no-friction at the wall-soil interfaces, indicate possibility of significant ground motion incoherency induced amplifications of local shear force and bending moment demands on the SMR exterior wall.

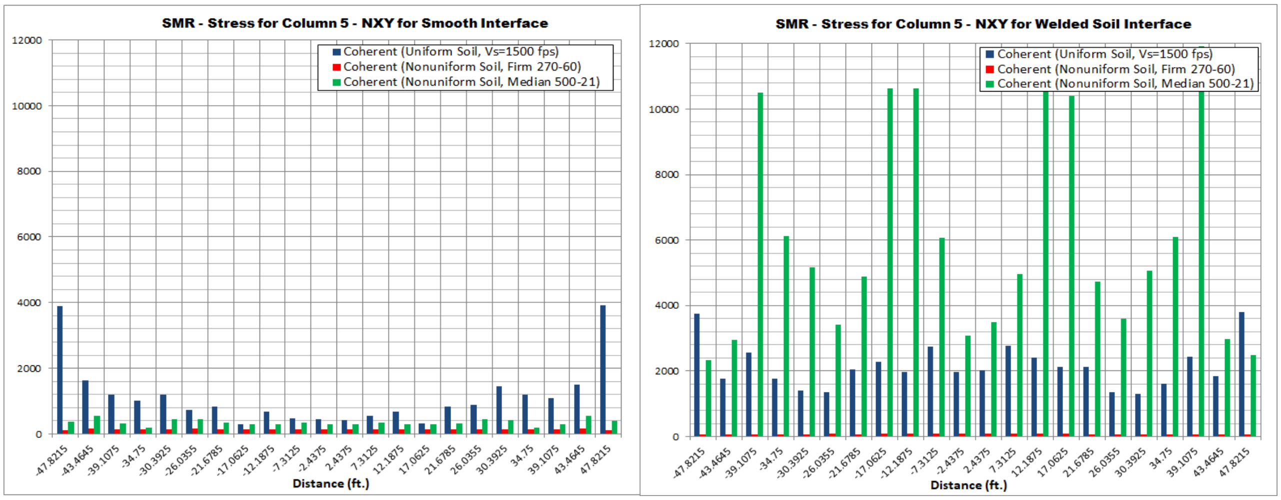


Figure 13 Column 5 NXY Shear Force in SMR Wall for Smooth (left) and Bonded (right) Interfaces

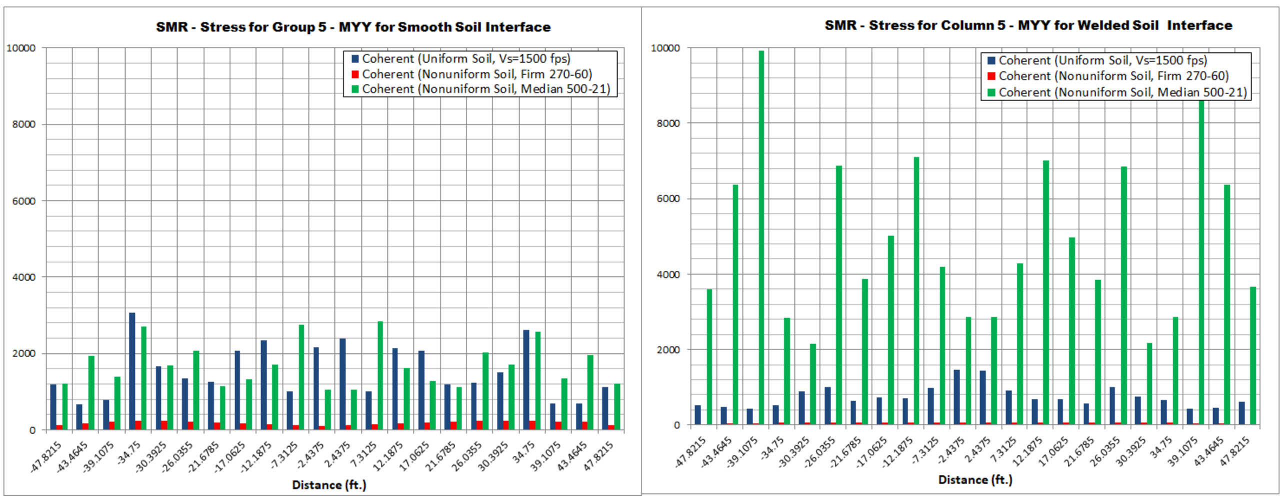


Figure 14 Column 5 MXX Moment in SMR Wall for Smooth (left) and Bonded (right) Interfaces

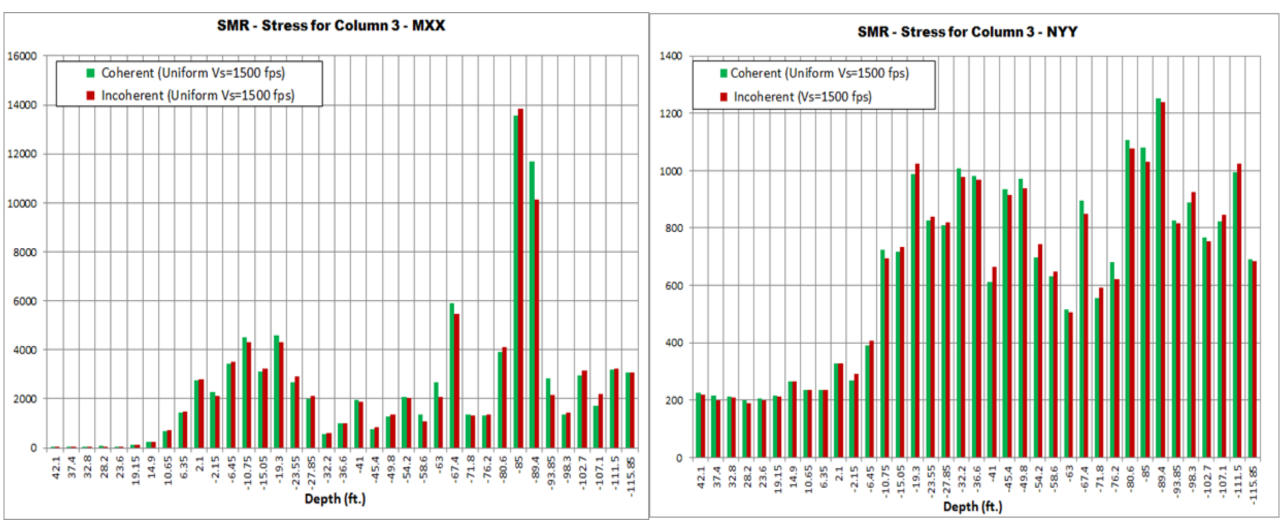


Figure 15 Column 3 MXX and NYY for Coherent and Incoherent Inputs for Uniform Soil Site

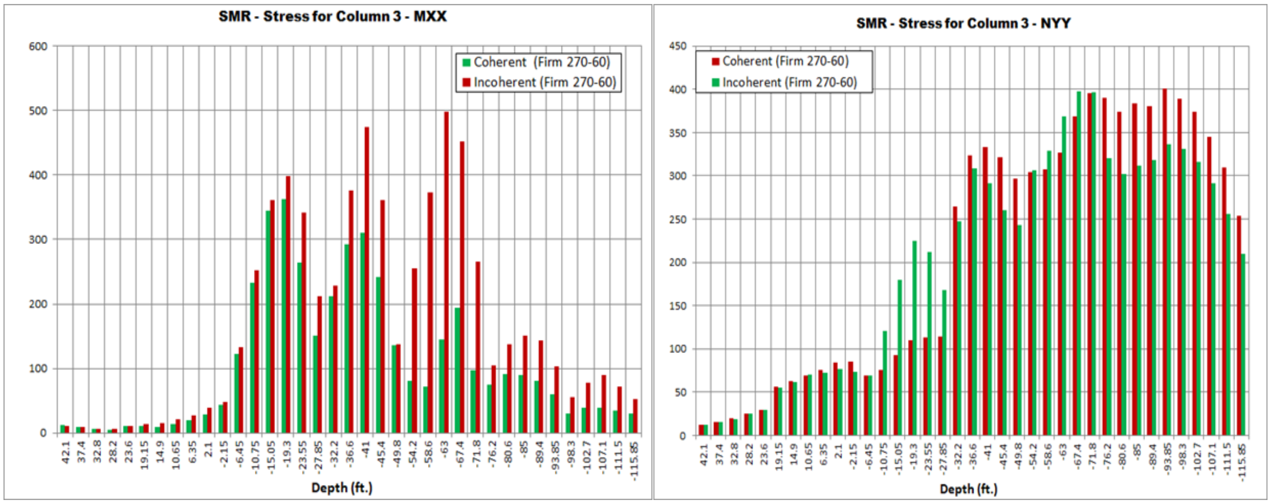


Figure 16 MXX and NYY for Coherent and Incoherent Inputs for 270-60 Deep Soil Site

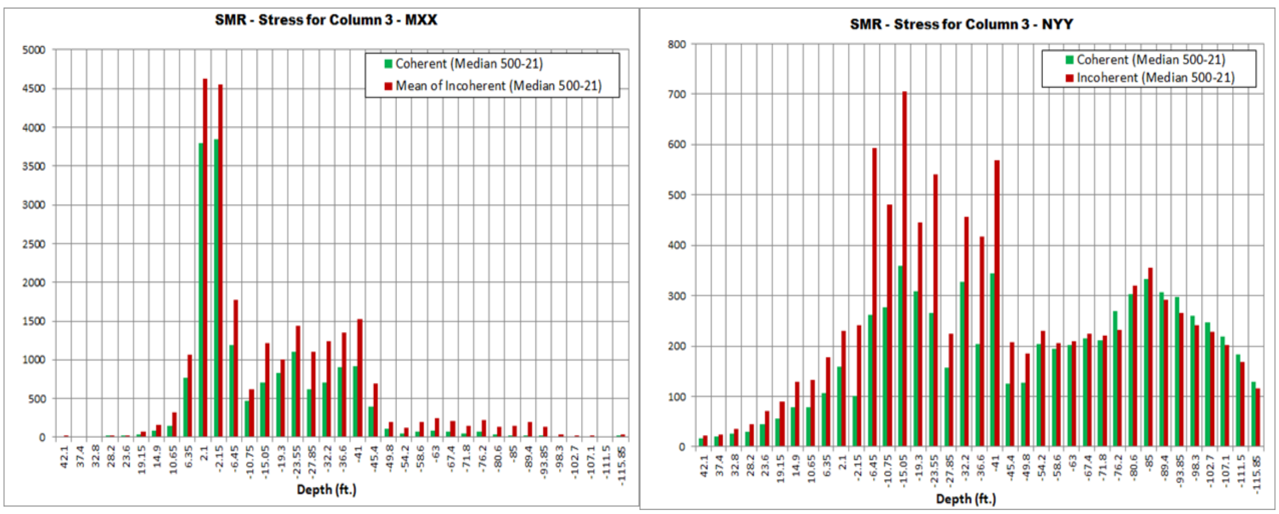


Figure 17 MXX and NYY for Coherent and Incoherent Motions for 500-21 Shallow Rock Site

LOW FREQUENCY FILTERING OF INCOHERENT MOTIONS

The lack of filtering the low-frequency (long-period) noise in the spatially varying incoherent ground motions may generate artifical quasi-static response of the SMR strucutre resulting in largly overestmated structural forces and moment demands. To illustrate how this low-frequency noise can affect the calculations of element stress results from incoherent SSI analyses, Figure 18 provides two comparisons of coherent and incoherent SSI analyses results for maximum bending moments MXX in the Column 3 vertical line (from top to bottom elevations) for the uniform soil site with Vs =1,500 fps. The left plot of Figure 18 compares the incoherent vs. coherent results that were calculated without filtering out the very low frequency noise. The right plot compares the incoherent vs. coherent results calculated by applying a Butterworth high-pass filter of order 5 with a 0.25 Hz corner frequency. The comparisons in Figure 18 show that the very low-frequency noise components may produce overly conservative estimates of the incoherent element force and moment demands in the SMR walls.

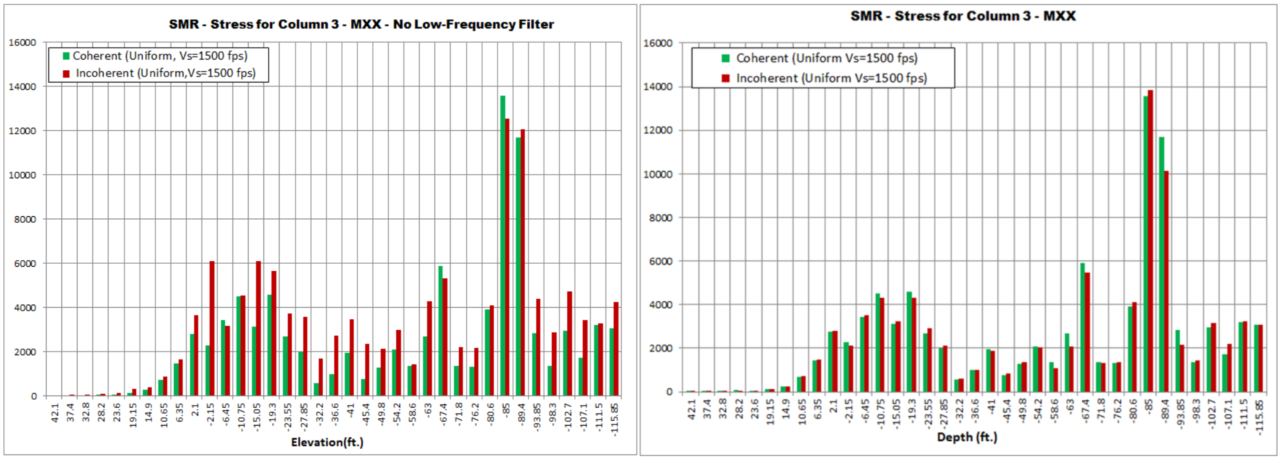


Figure 18 Comparisons of Column 4 Coherent and Incoherent MXX Responses Calculated Without (left) and With Low-Frequency Filtering, fc = 0.25 Hz (right)

The very low-frequency wave component filtering for the incoherent, spatially varrying motions is as important for obtaining physically realistic seismic responses under incoherent ground motions as is the low-frequency component filtering for the coherent motions using the baseline correction procedures. At the same time, it should the noted that the over filtering of the low-frequency components could be dangerous since could create unconservative SSI models. Expert judgment combined with adequate sensitivity studies is of a key importance.

To illustrate the effects of the filtering parametars on the incoherent element stress results, Figure 18 compares results of coherant and incoherent SSI analyses of 500-21 shallow rock profile for out-of plane shaer foces QXZ and horizontal membrane forces NXX on the Column 3 vertical line of wall shell elements (see Figure 12). The plots compare the computed maximum shell element responses from the coherent SSI analysis and two incoherent SSI analyses using a Butterworth high-pass filter of order n = 5, with a corner frequency of fc=0.25 Hz or corner period Tc = 4 sec and fc=0.50 Hz (or corner period Tc = 2 sec), respectively.

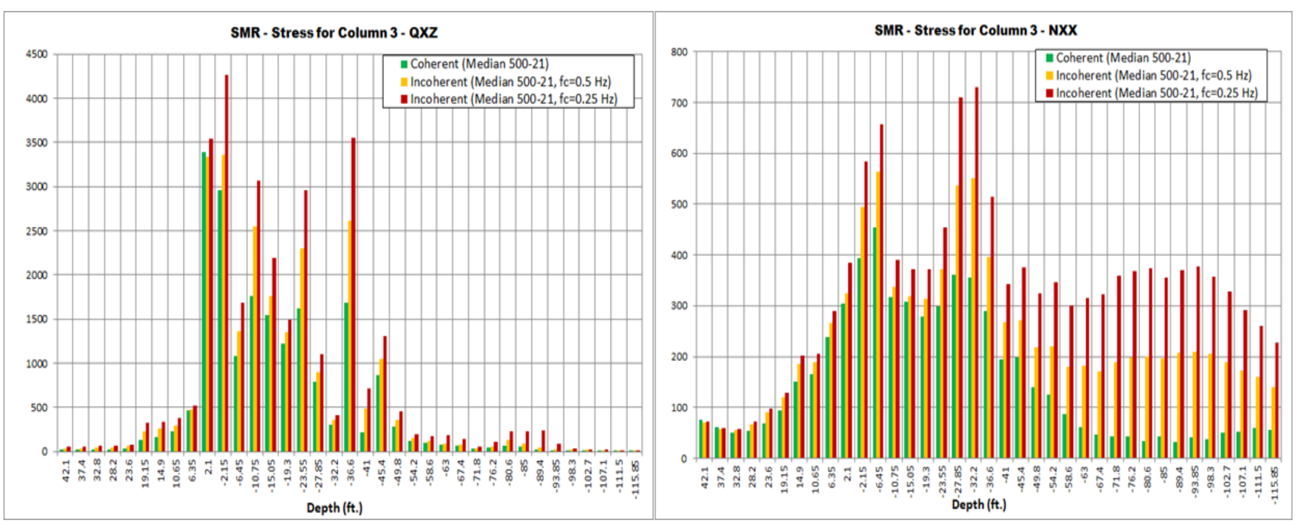


Figure 19 MXX and NYY for Coherent and Incoherent Inputs for 500-21 Shallow Rock Site

Based on the typical spatial dense arrays records, it appears that the application of a high-pass filter with a corner frequency fc= 0.25 Hz or corner priod Tc = 4 seconds is a reasonable assumption for the incoherent SSI analysis based on simulated spatially varying waves (Falamarz-Sheikhabadi and Zerva, 2019). Any available site-specific information related to the low-frequency wave components should be carefully and conservatively considered for the incoherent SSI modeling.

CONCLUDING REMARKS

The paper presents a study of the effects of motion incoherency based on comparisons of responses from coherent and incoherent SSI analyses performed for three different sites: an uniform soil with Vs = 1,500 fps; a deep soil, with a realistic increasing stiffness with depth (firm 270-60), and a highly nonuniform soil, with a shallow soil layer above rock (median 500-21). The comparisons shows that the SSI responses under both coherent and incoherent ground motions depend significantly on the site conditions, particularly for the 500-21 soil profile with a large abrupt change in stiffness. Due to the small SMR footprint, the effects of ground motion incoherency on the in-structure responses of the deeply embedded SMR are less significant. In general, motion incoherency induced some reductions of the ISRS amplitudes for most locations, especially for the fully bonded soil interface condition. The motion incoherency effects on the SMR embedded wall structural response can be more pronounced, specifically for highly nonuniform sites, such as the 500-21 soil profile with abrupt stiffness variation, where significant incoherency induced soil motion amplifications were observed.

The SSI analysis results for the two bounding conditions of the wall-soil interface, specifically, smooth no-friction interface and fully bonded interface, show that the modeling of the soil interface may significantly affect the estimates not only of the stress responses of the below grade walls, but also the overall in-structure responses of the deeply embedded SMR. For the highly nonuniform soil 500-21 the consideration of the bonded interface condition can result in 100% increase of ISRS amplitudes and up to 300-400% increase of the magnitudes of the SMR exterior wall forces and moments. On the other hand, the consideration of the bonded interface for the uniform and deep soil site conditions, can reduce ISRS amplitudes by 50% and reduce the SMR wall forces and moments by 20-50%.

The results of this study also showed the need for filtering out the very low-frequency or very long-period noise from the incoherent spatially varying motions to prevent generation of unrealistic quasi-static structural forces and moments in deeply embedded SMR structure. An appropriate low-frequency filtering is required for obtaining unrealistically high seismic demands in deeply embedded SMR walls. On the other hand, over-filtering of the low-frequency components should be avoided since it may result in unconservative structural force and moment results. Expert judgment combined with adequate sensitivity studies is of key importance.

It should be also noted that the seismic SSSI effects can largely affect the deeply embedded SMR responses as shown elsewhere (Ghiocel and Todovski, 2024).

REFERENCES

Abrahamson, N. (2007). Abrahamson, N. (2007). Effects of Spatial Incoherence on Seismic Ground Motions, *Electric Power Research Institute, Palo Alto, CA and US Department of Energy, Germantown, MD,* Report No. TR-1015110, December 2

Falamarz-Sheikhabadi, M. R and Zerva, A. (2019). Optimal Corner Frequency in High-Pass Filtering of Strong Ground Motions and Its Effect on Seismic Intensity, *Journal of Earthquake Engineering*, DOI: 10.1080/13632469.2019.1605947

Ghiocel, D.M. and Todorovski, L. (2024) Seismic SSSI Analysis for Deeply Embedded SMR Structure Founded on Different Nonuniform Soil Site Conditions, *SMIRT27 Conference, Division V*, Yokohama, Japan, March 3-8

Ghiocel Predictive Technologies (2023) ACS SASSI NQA Version 4.3 An Advanced Computational Software for 3D Dynamic Analysis Including Soil-Structure Interaction, *GP Technologies, Inc., User Manuals, Revision 9,* Pittsford, New York

NEDO (2022). TLR-33914A: BWRX-300 Advanced Civil Construction and Design Approach, Revision 2