Transactions of the SMiRT 27
Yokohama, Japan, March 3-8, 2024
Division III

SEISMIC SSI SENSITIVITY STUDY OF LARGE-SCALE NUCLEAR ISLAND USING SASSI HIGH PERFORMANCE COMPUTING (HPC)

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ABSTRACT

SASSI (Lysmer, et al., 1981) is a widely used software program in the nuclear industry for seismic soil-structure interaction (SSI) response analysis of nuclear power plants (NPP). However, in the past, the use of SASSI has been limited to structural finite element (FE) models with relatively small footprints and embedment due to the computational speed and memory requirements. To overcome this constraint, a new solver algorithm and high-performance computing (HPC) capabilities have been incorporated into a new and improved version of MTR/SASSI software (Tabatabaie, 2014) to allow effective analysis of large-scale SSI systems with detailed structural models.

The purpose of this paper is to present the results of seismic SSI response sensitivity studies performed for a nuclear island using the MTR/SASSI HPC program. Three soil profiles designated as soft, medium and hard soil cases were analyzed. For all three soil cases, one set of three-component acceleration time histories was selected as input motions at free-field ground surface. The purpose of the study was to identify the most penalizing soil condition between the three different soil cases in terms of in-structure response spectra (ISRS) and internal force resultants for the shear walls as well as percentage uplift of the foundation base slab for each soil case.

SOIL PROFILE AND PROPERTIES

Three semi-infinite soil profiles with uniform soil properties corresponding to soft, medium and hard soil cases were used for the sensitivity study. Table 1 summarizes the soil properties for the three soil cases. The soil properties shown in Table 1 are considered strain compatible; therefore, no further adjustment of these properties was performed to account for the site response and SSI effects.

Table 1. Soil Properties for Three Soil Cases

Property	Units	Soil Case		
		Soft	Medium	Hard
Shear wave velocity	m/s	300	1,100	3,000
Compression wave velocity	m/s	1,261	2,694	6,245
Unit weight	N/m3	19,620	21,582	24,525
Poisson's ratio	-	0.47	0.40	0.35
Material damping	Decimal	0.05	0.04	0.03

INPUT MOTIONS

One set of three-component (two horizontal and one vertical) spectrally matched and statistically independent synthetic acceleration time histories were used as input motions for the SSI sensitivity analyses. The input motions were specified at the free-field ground surface and used for all three soil cases. The acceleration time histories of the three components of input motions and their 5-% damped acceleration response spectra compared with the Design Earthquake Event (DEE) target spectra are shown in Figure 1.

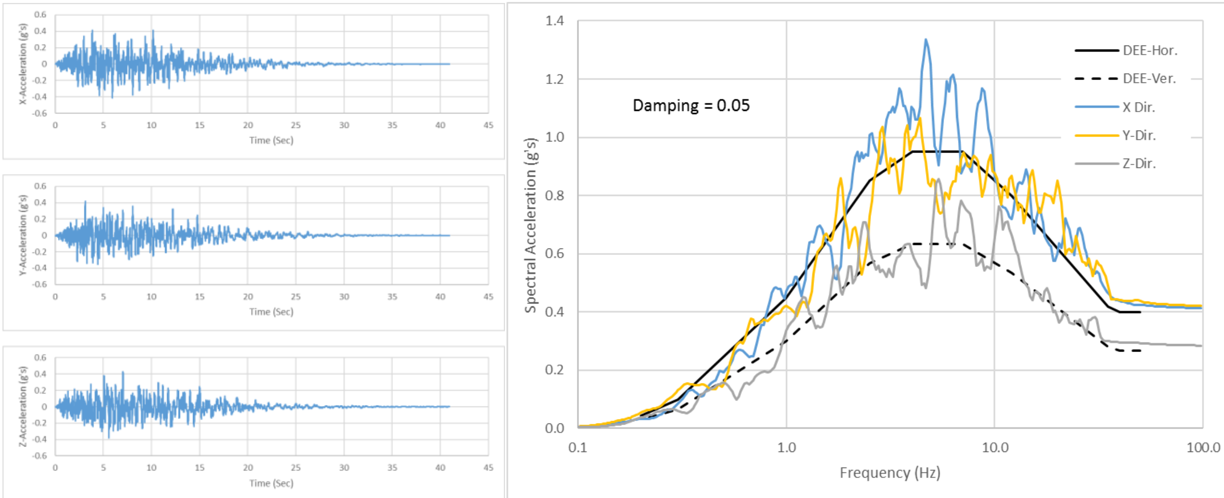


Figure 1. Acceleration Time History and Response Spectra of Input Motions

STRUCTURAL MODEL

The structure model consists of a nuclear island incorporating the reactor building (RB), fuel building (FB) and safeguard buildings (SB) 1, 2/3 and 4, all of which share a common base slab. The configuration and overall dimensions of the nuclear island footprint is shown in Figure 2, The nuclear island was embedded approximately 12.5m below the ground surface. For the sensitivity analysis, the ground surface was set at El. -10.5m.

A detailed three-dimensional finite element (FE) structural model of the nuclear island was provided in ANSYS. For SSI analysis, the ANSYS model was converted “as is” to a SASSI structural model. The model conversion was validated by performing dynamic analysis of the nuclear island on a fixed-base condition and comparing the results in terms of the dominant structural frequencies and ISRS calculated at selected locations in the structure.

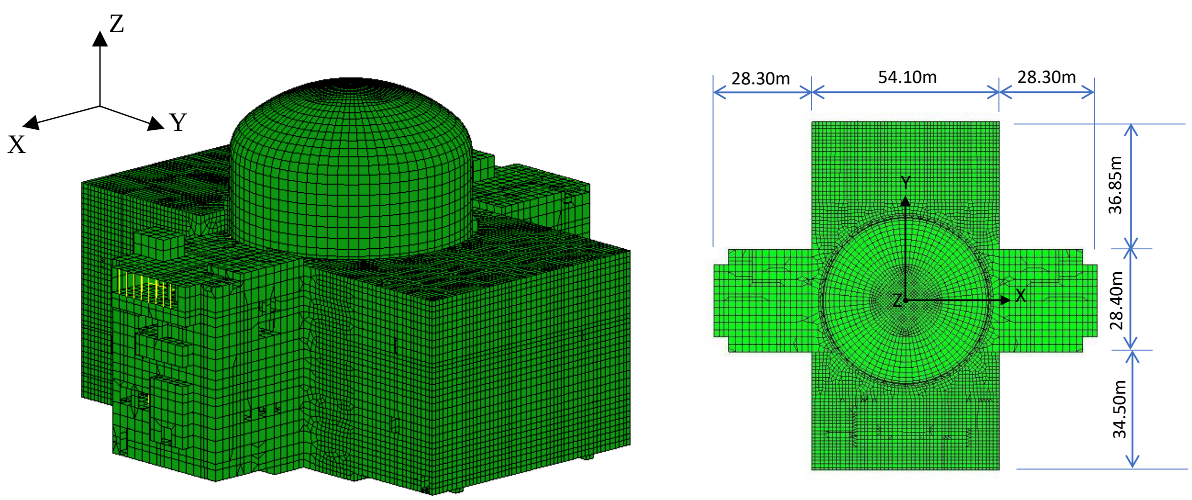


Figure 2. FE Model of Nuclear Island Structure

The structure model consists of about 75,760 shell elements representing the concrete floors, roof, walls and base slab -- all of which are modeled as flexible members. Some elements of the internal structure, such as the equipment supports, are modeled by beam elements.

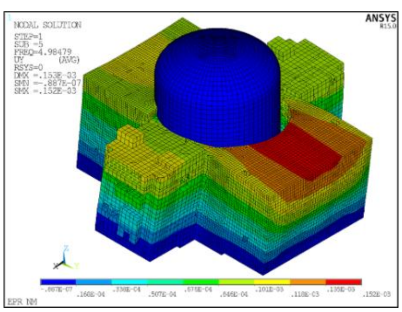
VALIDATION OF STRUCTURAL MODEL CONVERSION

Dynamic response analysis of the nuclear island was performed assuming a fixed-base condition to validate the structural model conversion from ANSYS to SASSI and to gain insight into the dynamic behavior of the structure. The results included modal properties and ISRS from ANSYS as well as frequency response transfer functions and ISRS from MTR/SASSI.

For the ANSYS analysis, all nodes at the base of the structure were constrained to a master node having a large mass and located at the center of the foundation. This node was then excited by simultaneously applying the three components of input motions in the X-, Y- and Z-directions. The mass of the master node was set to be 3 to 4 orders of magnitude larger than the total mass of the structure to ensure that the structure itself would not affect the movement of the master node. The ANSYS analysis was performed using the time history modal superposition method.

For the MTR/SASSI analysis, the fixed-base structure was analyzed using the FBASE module. This module uses the same structural model developed in the HOUSE program for the SSI analysis except that all the nodes at the base of the structure are restrained in the X-, Y- and Z-directions, and the structure is excited simultaneously by three components of input motion applied at the restrained nodes. This procedure is very efficient and simulates an infinitely rigid support. The analysis is performed in the frequency domain.

The first 40 modes of the fixed-base structure were extracted from ANSYS. The first seven modes, together with the mode shape with the highest participation factor, are shown in Figure 3. As shown in Figure 3, the frequencies of the dominant X and Y modes range between 5.0 to 6.2 Hz. The frequency of the vertical mode is above 10 Hz and is not shown in Figure 3. The comparable MTR/SASSI modes observed from typical transfer functions calculated in the X-, Y- and Z-directions at several key locations in the structure show very good agreement with the ANSYS results. See, for example, the typical transfer functions at Node 69219 in SB 2/3 building, as shown in Figure 4 (see Figure 5 for location of Node 69219).



Mode No.	Frequency (Hz)	Mode Participation Factor		
		X-Dir	Y-Dir	Z-Dir
1	4.982	0.062	0.044	0.000
2	5.012	0.051	0.053	0.000
3	5.373	0.309	0.002	0.000
4	5.416	0.053	0.000	0.000
5	5.614	0.002	0.312	0.000
6	6.187	0.000	0.075	0.000
7	6.189	0.000	0.028	0.000

Figure 3. ANSYS Modal Properties, Fixed-Base Model

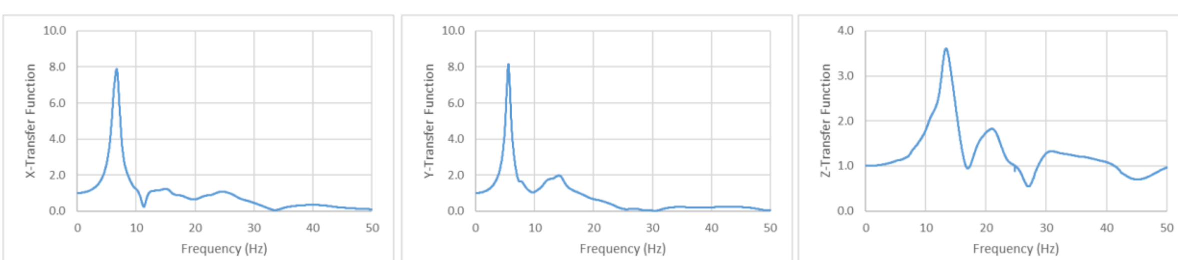


Figure 4. MTR/SASSI Transfer Functions at Node 69219, Fixed-Base Model

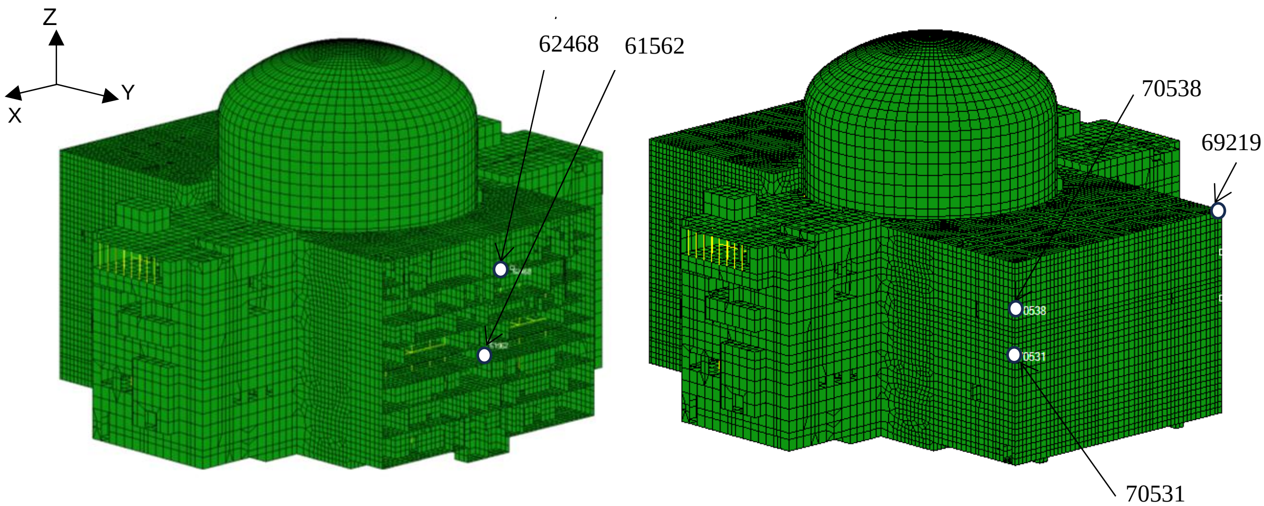
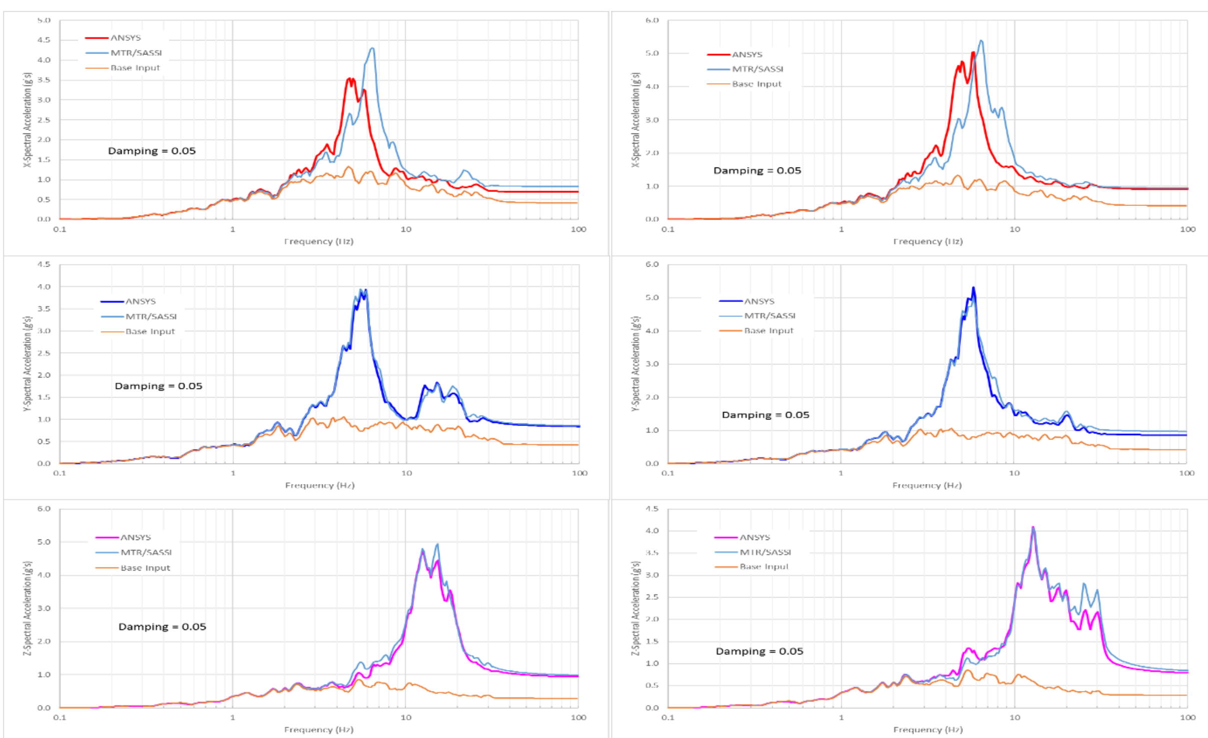


Figure 5. Location of Selected Nodes for Response Output

In addition to the structural modes, response of the fixed-base structure in terms of 5%-damped ISRS was calculated from ANSYS and SASSI at several selected locations in the structure. Figure 6 shows comparisons of typical ISRS results at Nodes 61562 and 62468 (for location of nodes, refer to Figure 5).

As seen in Figure 6, the results for the Y- and Z-direction responses show very good agreement between ANSYS and MTR/SASSI models. In the X-direction, the overall shape of the spectra between ANSYS and MTR/SASSI shows good agreement except for the amplitude and frequency of the dominant peak of ANSYS which are somewhat lower than those of MTR/SASSI.



Node 61562 Node 62468

Figure 6. Comparison of ANSYS vs. SASSI ISRS, Fixed-Base Model

The differences observed between the results of ANSYS and MTR/SASSI fixed-base models appear to be larger than in our previous experience dealing with such large-scale structural models. Nonetheless, the results are close enough to confirm the accuracy of the model conversion given the differences between the two codes.

SSI ANALYSIS

The SSI sensitivity analysis of the nuclear island was performed using the MTR/SASSI HPC Program. By incorporating a new solver algorithm and HPC capabilities, as discussed earlier, this new and improved version of the MTR/SASSI program allows large-scale SSI systems with detailed structural models with large foundation footprints and embedment to be effectively analyzed on computer clusters. Several NPP structures have been previously analyzed using this program, including a large nuclear island with over 50,000 direct interaction nodes (Tabatabaie, et al., 2011).

The SSI model of the nuclear island was completed by adding soil layers to the MTR/SASSI structural model developed and validated above. The structure was embedded below the ground surface (see Figure 7). This required excavated soil to be modeled for the SASSI analysis, as shown in Figure 8. The SSI analysis was performed using the direct method in SASSI (i.e., all excavated soil nodes were specified as interaction nodes). The subtraction method, despite its faster runtime, was not utilized to avoid any numerical issues previously reported from the use of this method in SASSI (Tabatabaie, 2013).

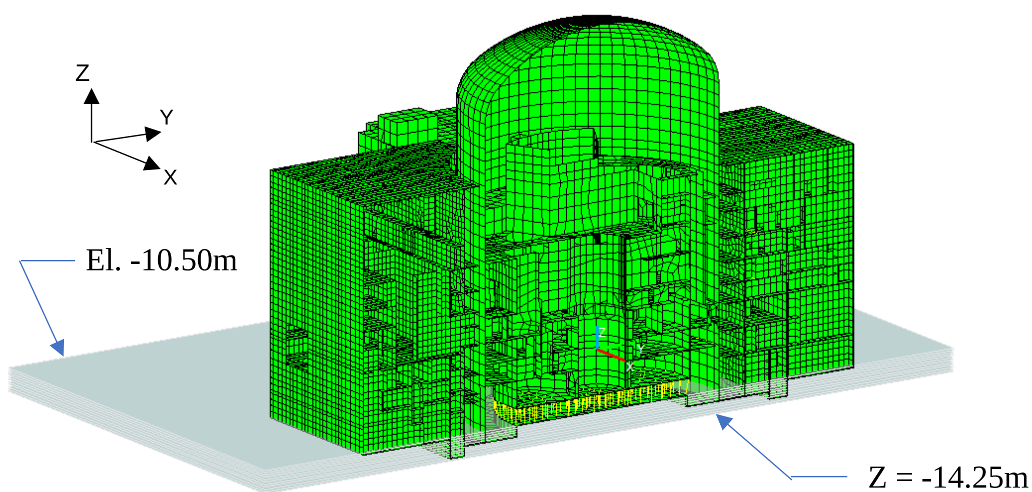


Figure 7. Basement Cut View of MTR/SASSI SSI Model

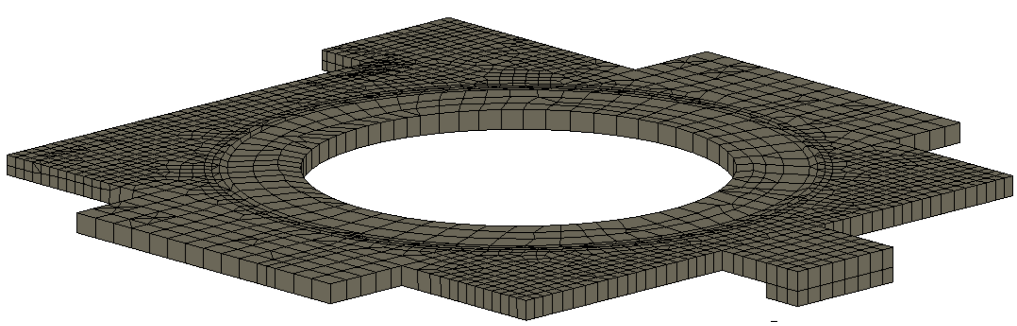


Figure 8. Excavated Soil Model

The SSI model of the nuclear island was subjected to three components of input motion in the X-, Y- and Z-directions applied simultaneously at the free-field ground surface. For the SSI analysis, the seismic wave field was assumed to consist primarily of vertically propagating shear and compressional waves with the control motion specified at the free-field ground surface. It is noted that because of the embedment, some reduction of the input motion with depth was expected at the interaction nodes below El. -0.25m. The SSI analyses were performed for three soil cases corresponding to the soft, medium, and hard soil profiles.

In addition to the in-structure response, the percent base uplift of the nuclear island was evaluated by performing dead load analysis and combining the results with those of the seismic SSI analysis. For the deadload analysis, the same SSI model for each soil case was used – except that instead of applying seismic excitations, the model was subjected to gravity loads (nodal mass times 1g acceleration) at each node and analyzed at a very low frequency. The vertical soil reaction forces for each base node from gravity loads and seismic excitations were combined to calculate the total reaction force at each time step. If the total resultant reaction force at a node is positive, then the node is in tension. The positive and negative reaction forces were added up at all base nodes and used to calculate the percentage uplift versus time.

DISCUSSION OF RESULTS

The results of SSI analysis of the nuclear island obtained at several locations in SB 2/3 are compared for the three soil cases to identify the most penalizing soil case. The comparison of the results includes maximum acceleration, in-structure response spectra, maximum base shear force and foundation uplift, as discussed below.

Maximum Accelerations

Table 2 compares the maximum accelerations calculated at six locations in SB 2/3 for the soft, medium and hard soil cases.

The selected locations include two adjoining wall nodes – Nodes 61562 and 62468 at Z = 11.75m and Z = 20.75m (see Figure 5) – and two interior floor slab nodes – Nodes 70118 and 70531 at Z = 11.75m, and Nodes 70125 and 70538 at Z = 20.75m (see Figure 9).

A review of the typical results in Table 2 shows that the maximum acceleration responses increase with stiffness of the soil profiles in all three X-, Y- and Z-directions at all locations. Thus, in terms of maximum acceleration, the hard soil case controls the response.

Table 2. Maximum Acceleration Response at Selected Adjoining Wall and Floor Slab Nodes (g's)

Node No.	Analysis Case								
	Soft Soil			Medium Soil			Hard Soil		
	X Dir.	Y Dir.	Z Dir.	X Dir.	Y Dir.	Z Dir.	X Dir.	Y Dir.	Z Dir.
61562	0.24	0.32	0.49	0.58	0.68	0.81	0.66	0.84	0.90
62468	0.24	0.32	0.37	0.60	0.79	0.56	0.69	0.97	0.70
70118	0.25	0.29	0.30	0.55	0.54	0.43	0.62	0.65	0.53
70531	0.24	0.35	0.35	0.56	0.62	0.54	0.67	0.63	0.65
70125	0.23	0.32	0.30	0.65	0.69	0.48	0.74	0.81	0.60
70538	0.26	0.37	0.37	0.62	0.76	0.59	0.75	0.77	0.71

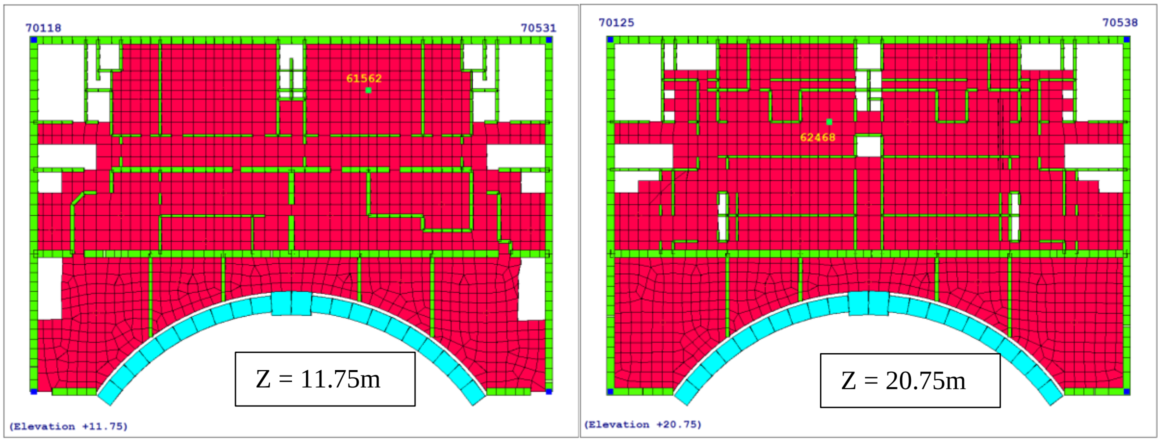
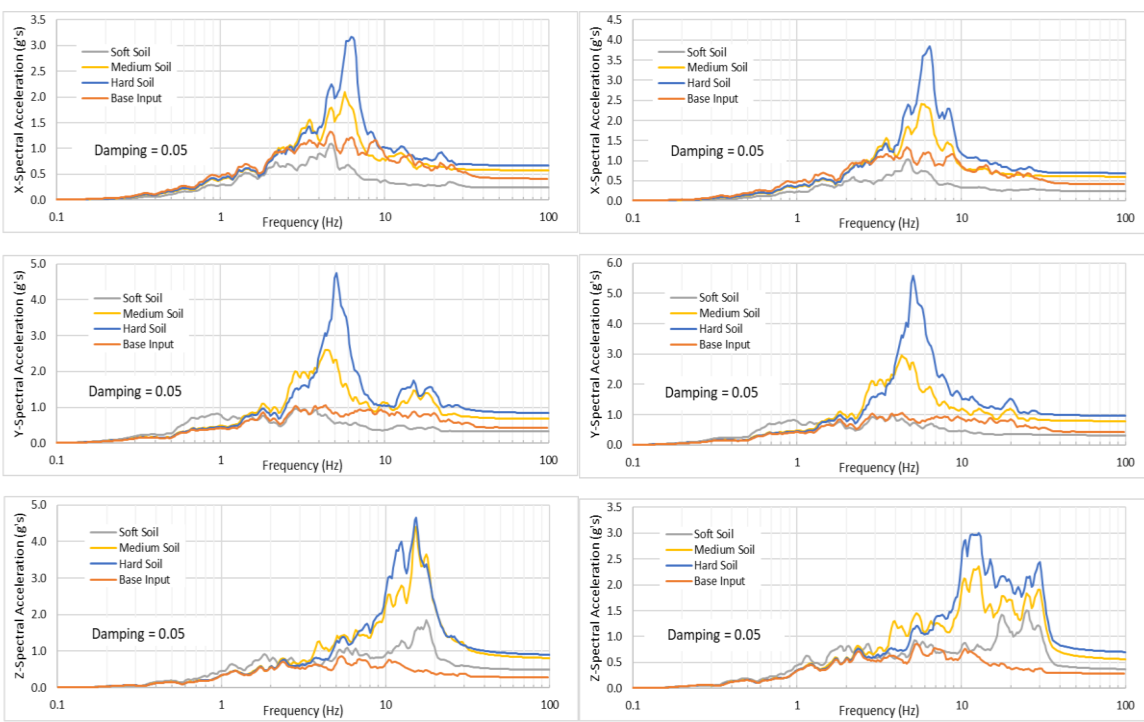


Figure 9. Location of Response Output at Floor Slab Nodes

In-Structure Response Spectra

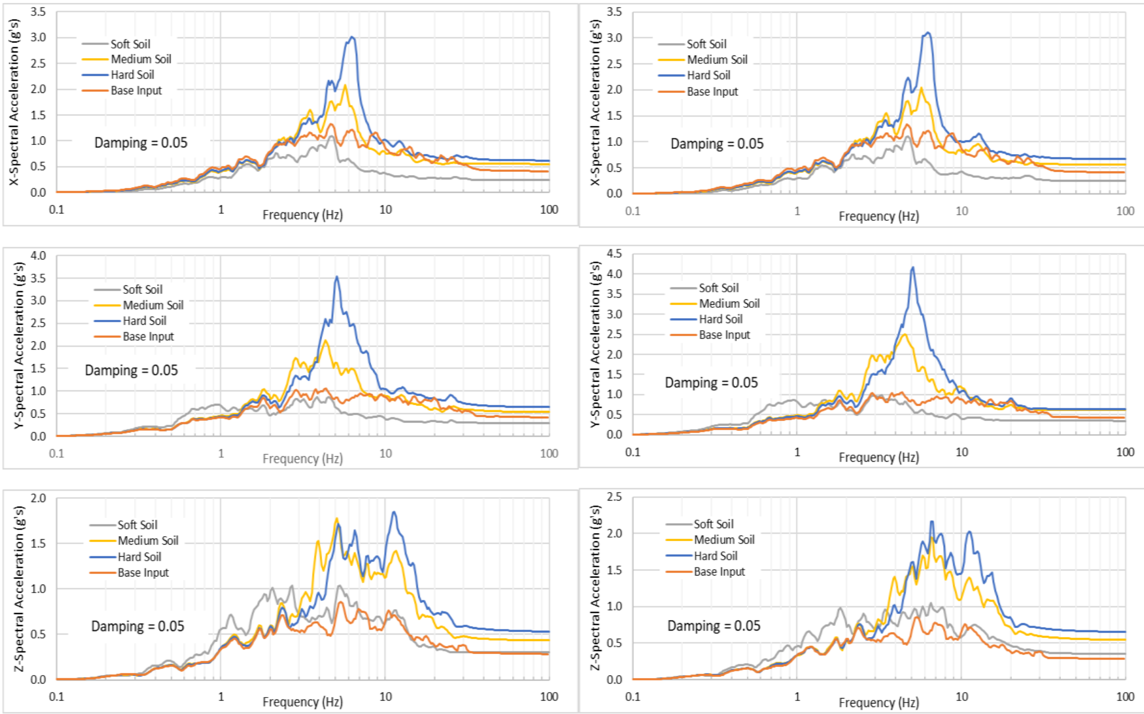
The ISRS obtained using the three soil cases are compared in Figures 10, 11 and 12 for the six locations mentioned above.

For the typical interior floor slab nodes (70118, 70531, 70125 and 70538) shown in Figures 11 and 12, the spectral accelerations from the hard soil case exceed those from the soft and medium soil in all three X-, Y- and Z-directions and at all frequencies and locations except for a small frequency band between about 3 to 5 Hz where the results from the medium soil mainly in the Y- and Z-directions slightly exceed those of the hard soil case.



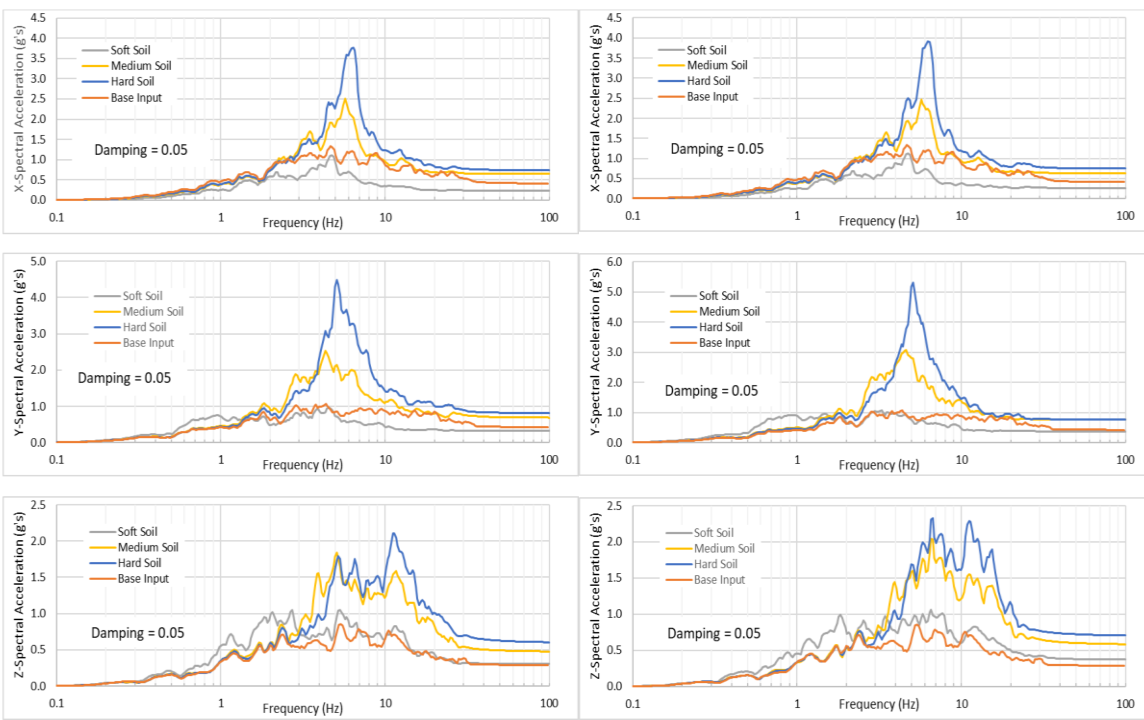
Node 61562 Node 62468

Figure 10. Comparison of ISRS for Three Soil Cases, Adjoining Wall Nodes



Node 70118 Node 70531

Figure 11. Comparison of ISRS for Three Soil Cases, Floor Slab Nodes, Z = 11.75m



Node 70125 Node 70538

Figure 12. Comparison of ISRS for Three Soil Cases, Floor Slab Nodes, Z = 20.75m

For the adjoining wall nodes (61562 and 62468) shown in Figure 10, the results from the hard soil case exceed those of the soft and medium soil at all frequencies above 5 Hz. At frequencies below 5 Hz, either the soft or medium soil mainly governs the response. Therefore, if the focus of the most penalizing soil case is for equipment response at frequencies above 5 Hz, the hard soil will control the spectral response.

Maximum Resultant Base Shear Force

Table 3 summarizes the maximum resultant base shear forces for the exterior East (E), North (N) and West (W) walls of SB 2/3 calculated for the three soil cases (for the location of the walls, refer to Figure 13). A comparison of the results shown in Table 3 indicates that there is not a significant difference between the results of the three soil cases for the East and West walls. With respect to the North wall, the hard soil case results in higher base shear as compared to the soft and medium soil cases. It is noted that for the soft soil case, the reported results for the East and West walls are the average values calculated for the two walls. In terms of base shear forces on the exterior walls of the SB 2/3, the hard soil appears to be the most penalizing soil case.

Table 3. Maximum Resultant Exterior Wall Base Shear Forces (N), SB 2/3

Wall	Soil Case		
	Soft	Medium	Hard
East (E)	1,612,925	1,600,452	1,778,000
North (N)	1,513,540	1,907,136	2,236,882
West (W)	1,612,925	1,560,543	1,410,237

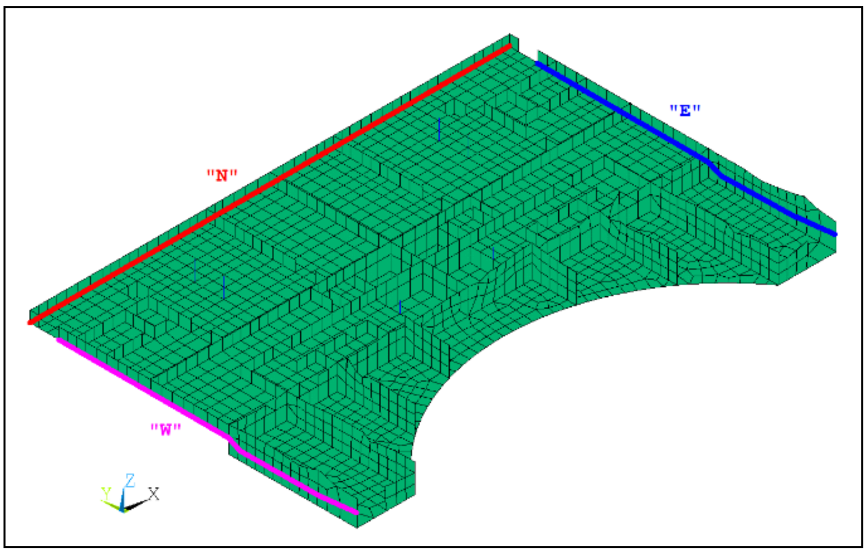


Figure 13. Base of Exterior Walls of SB 2/3 Where Base Shear is Output

Base Uplift

Figure 14 shows the percentage of base uplift versus time for the soft, medium and hard soil cases. As seen in Figure 14, the maximum base uplift for the soft, medium and hard soil cases are about 15, 16 and 24 percent, respectively, with the hard soil case being the most penalizing soil profile.

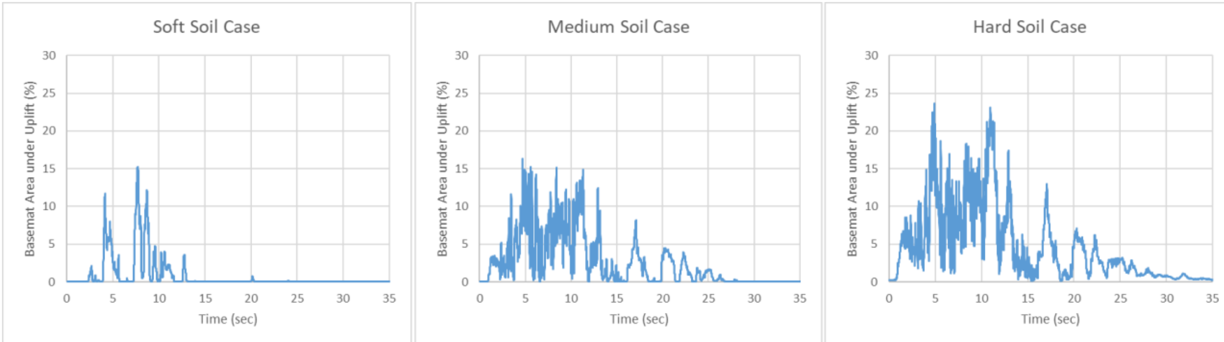


Figure 14. Percentage Uplift vs. Time

CONCLUSIONS

The SSI responses of the nuclear island in terms of the maximum accelerations, ISRS and wall stresses calculated at several locations in SB 2/3 were presented in this paper for three different soil cases: soft, medium and hard. Based on a comparison of the results presented above, it is concluded that:

- The hard soil case is the most penalizing soil profile when maximum accelerations are considered.
- The hard soil case is the most penalizing soil profile when spectral frequencies above 5 Hz are considered. For frequencies below 5 Hz, either the soft or medium soil profile controls the spectral accelerations.
- In terms of the wall stresses, there is no significant difference between the results of the three soil cases for the East and West walls. For the North wall, the hard soil case controls the base shear.
- In terms of the base uplift, the hard soil case is the most penalizing soil profile with maximum uplift of about 24 percent.

ACKNOWLEDGEMENT

The author would like to acknowledge the contributions of AREVA NP France and ABS Consulting USA for providing the data and ANSYS results used in this study.

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