# Detailed Finite Element Modeling of US EPR™ Nuclear Island for Seismic SSI Analysis

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## ABSTRACT

Seismic soil-structure interaction (SSI) analysis of nuclear power plants (NPPs) is often performed in the frequency domain using a lumped-mass stick and/or coarse finite element (FE) model of the structure. These models are designed to capture the global dynamic response of the system. The results provide the inertia forces for foundation stability assessment, which also serve as input to a static detailed FE model of the structure for design. The in-structure response spectra is calculated from a separate dynamic analysis of a detailed structural model with fixed base, excited by either the base motion developed from SSI analysis or, more often, the inclusion of single-degree-of-freedom (SDOF) oscillators representing the local response in the stick/coarse FE SSI models. With the recent advances in computer software and hardware technology, it is now possible to perform SSI analysis of detailed structural models in the frequency domain.

This paper presents the results of the seismic SSI analysis of the US **EPR™** nuclear island (NI) using both stick and detailed FE representations of the structure. The soil profile corresponds to a medium stiff soil case used for the Standard Design. Because the **EPR™** NI is a complex, un-symmetric structure, the stick model consists of multiple interconnected sticks developed and calibrated against a detailed FE model of the structure with a fixed base. Both models are analyzed using MTR/**SASSI** [1]. The results of the detailed FE model in terms of maximum accelerations and response spectra, as well as total interstory forces and moments, are calculated and compared against those of the lumped-mass stick model.

## INTRODUCTION

The US **EPR™** Standard Design is an advanced NPP currently under development by AREVA. The plant consists primarily of a nuclear island (NI) and several other significant structures outside of and in close proximity to the NI. The NI structures consist of the Reactor Building (RB) [which incorporates the Reactor Containment Building (RCB), Reactor Shield Building (RSB), and Reactor Building Internal Structures (RBIS)], Fuel Building (FB), Safeguard Building 1 (SB1), Safeguard Building 2/3 (SB2/3), and Safeguard Building 4 (SB4) - all of which share a common foundation basemat. The NI is embedded approximately 11.6 meters below the ground surface. Significant structures outside the NI include the Turbine Building (TB), Nuclear Auxiliary Building (NAB), Radwaste Building (RWB), Emergency Power Generating Buildings (EPGB); and Emergency Service Water Buildings (ESWB). Figure 1 shows the layout of the **EPR™** plant.


**Figure 1. Layout of EPR™ Plant**

The original seismic SSI analysis of the **EPR**™ NI structures for the Standard Design Certification was performed using a lumped-mass stick model, with floor diaphragms assumed to be rigid. Embedment effects were considered by modeling the basement walls with rigid beams connected at the floor elevations with rigid lateral links. A total of eleven generic soil profiles, ranging from soft to stiff soil to hard rock, and three associated ground motions representing Soft, Medium and Hard rock motions were used for the SSI analyses, with the results enveloped for design. With this approach, the stick model captures the global dynamic SSI response of the system, and the results provide the inertia forces for foundation stability assessment, which also serve as input to a static detailed FE model of the structure for design.

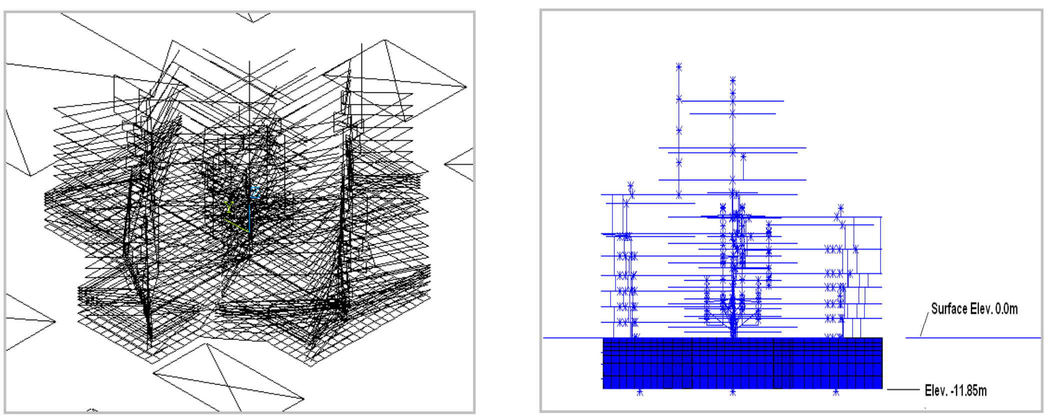
From the analysis progression, a detailed FE model of the NI structures was developed for SSI analysis. This model would address several key design issues, such as the effects of basemat, wall and floor flexibilities, and the effects of concrete cracking. The same FE structural model was employed in the SSI analysis using MTR/**SASSI** [2], and in the stress analysis using ANSYS [3]. This facilitated the exchange of data between the two models and helped eliminate potential errors associated with cross-platform model updating.

The development of the lumped-mass stick and detailed FE models of the NI structures are described below, followed by a comparison of the two models in terms of global dynamic forces and accelerations, and total interstory shear forces and overturning moments. Both models have the same below grade basement geometry and configuration.

## STRUCTURAL MODELS

### Lumped-Mass Stick Model

A 3-D lumped-mass stick model of the embedded NI structures, shown in Figure 2a, was developed for SSI analysis using MTR/**SASSI**. An elevation view of this model is shown in Figure 2b. The model consists of multiple interconnected sticks representing the walls and columns between the structures' principal floor elevations. To model embedment effects, horizontal rigid beams were added along the excavation face at soil layer interfaces where the NI walls bear against soil. These beams share common nodes with the soil interaction nodes. The beams are then connected with rigid links to the FB and SB2/3 shield sticks, and the SB1 and SB4 sticks to provide lateral support from side soils, and to transfer forces from the side soils to the sticks.

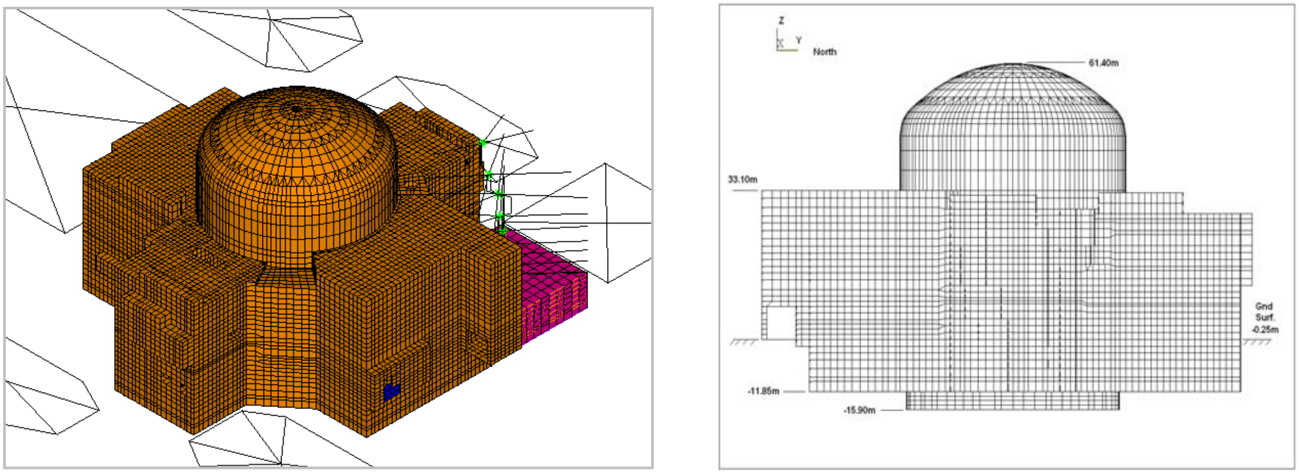



a) Isometric View b) Elevation View

**Fig 2 – MTR/SASSI Stick Model of NI Structures**

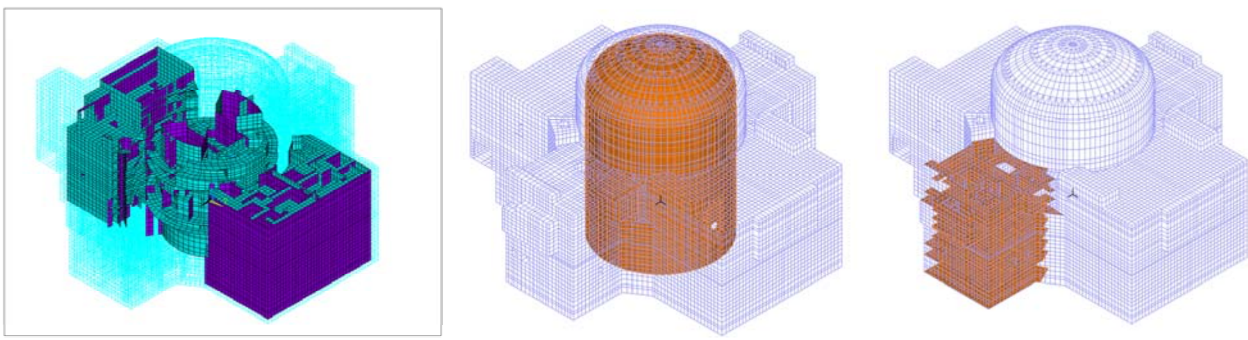
### Detailed FE Model

A 3-D detailed FE model of the NI was first developed in ANSYS and then converted to MTR/**SASSI** for SSI analysis. Isometric and elevation views of this model are shown in Figures 3a and 3b, respectively. The FE model incorporates all the major details of the NI structures, including the Reactor Building Internal Structures (RBIS), Reactor Containment Building (RCB), Reactor Shield Building (RSB), Fuel Building (FB), Safeguard Buildings 1, 2/3 and 4 (SB 1, SB 2/3, SB 4), Fuel Shield Building (FSB) and Safeguard Shield Building (SSB). The FE model consists mainly of solid/shell elements representing the concrete floors, walls and basemat - all of which are modeled as flexible members. The NSSS, major equipment supports, and polar crane are modeled by beam elements. Figure 4a shows the internal details of the RBIS, FB, and SB 2/3. Figures 4b and 4c show FE mesh of the RCB and SB 1 floor and roof slabs.




a) Isometric View b) Elevation View

**Fig 3 – Detailed FE MTR/SASSI Model of NI Structures**



a) RBIS, FB and SB 2/3 b) RCB c) SB 1 Floor and Roof Slabs

**Fig 4 – Details of NI Structures**

The NI foundation and excavated soil models are shown in Figures 5 and 6, respectively. All basement walls are connected to side soils, with the exception of the walls adjacent to the NAB and Access Building (AB). A reinforced concrete tendon gallery extends down from the bottom of the base of the RCB to an approximate elevation of -15.90 meters. The ground surface elevation is set at -0.25 meters and the bottom of the NI basemat at an approximate elevation of -11.85 meters.

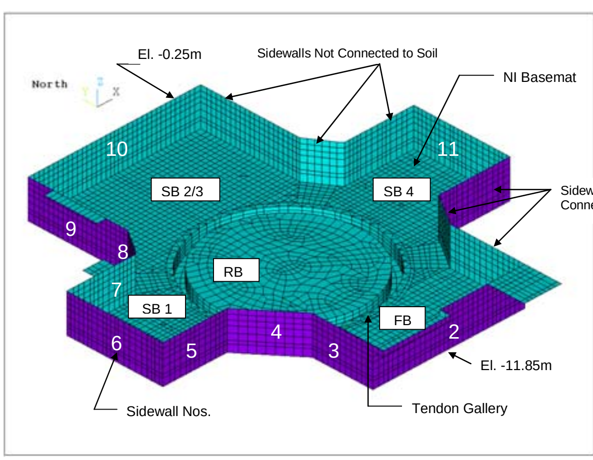



**Fig 5 – NI Foundation Model**

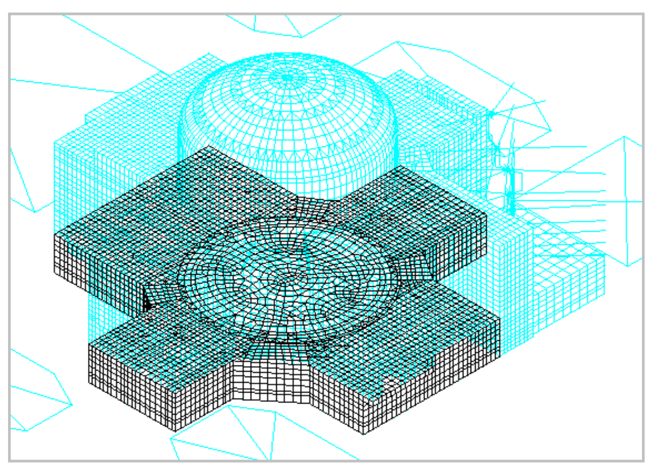


**Fig 6 – Excavated Soil Model**

## SOIL PROFILE AND PROPERTIES

The soil profile used in the SSI analysis of both the stick and detailed models corresponds to Soil Case 2sn4u, which is one of the eleven generic soil cases considered in this study (see Figure 7). It consists of a 26.6 meter-thick layer of medium stiff soil deposit ($V_s$=500 m/s, $V_p$=1,225 m/s, $\gamma$=17.28 kN/m$^3$, $\beta_s$=0.04 and $\beta_p$=0.0133) over soft rock formation ($V_s$=1,200 m/s, $V_p$=2,939 m/s, $\gamma$=18.85 kN/m$^3$, $\beta_s$=0.01 and $\beta_p$=0.033). The ground water table is set at approximately 0.33 meters below grade. The soil layer is subdivided into 22 sublayers with thicknesses matching the finite element grid of the NI basement walls in order to meet the minimum passing frequency of $V_s$/5h, where $V_s$ is the shear wave velocity of the foundation support media and h is the smallest element size in the soil model.

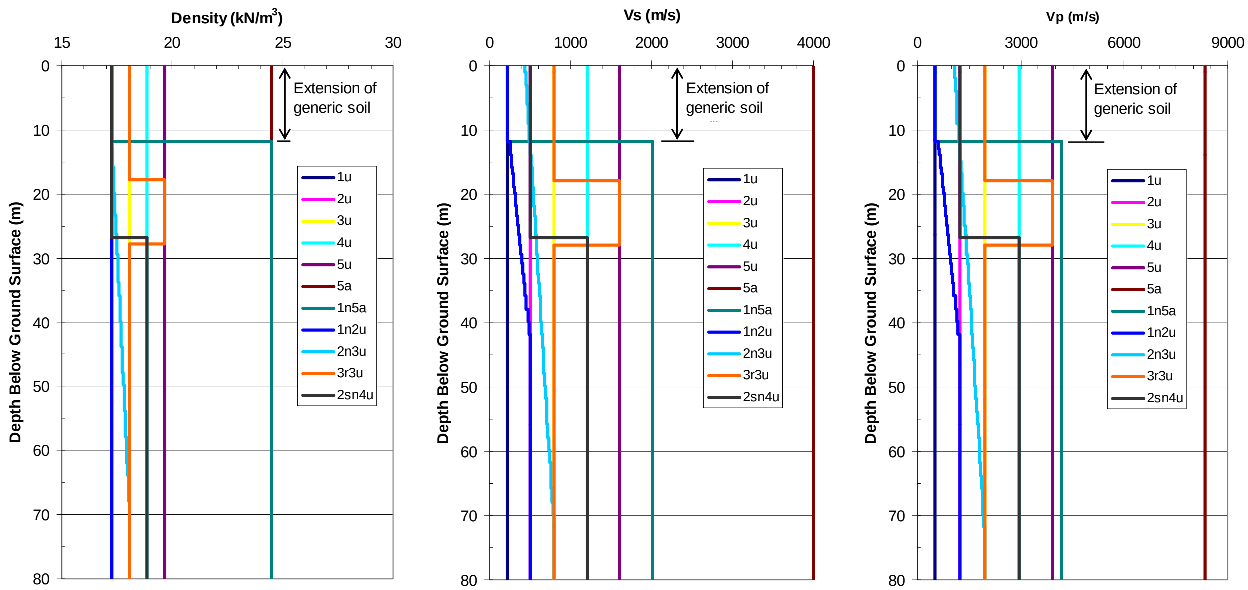
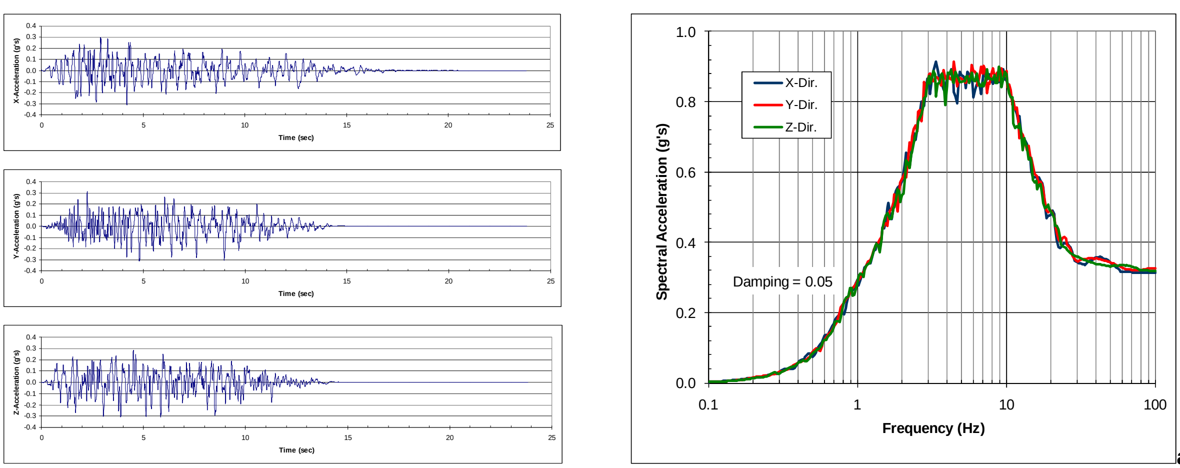



**Fig. 7 – Generic Soil Profiles and Properties**

## REFERENCE MOTIONS

The reference motions used for the SSI analysis consist of one vertical and two horizontal components of the EUR Medium motion (EURM). This motion is specified as full-soil column, free-field outcrop motion at the base of the NI basemat. The EURM motion has a maximum acceleration of 0.3 g. Figure 8a shows the acceleration time histories of the EURM motion in the x-, y- and z-directions. The time histories have a time step of 0.005 seconds. The acceleration response spectra of these motions are shown in Figure 8b.



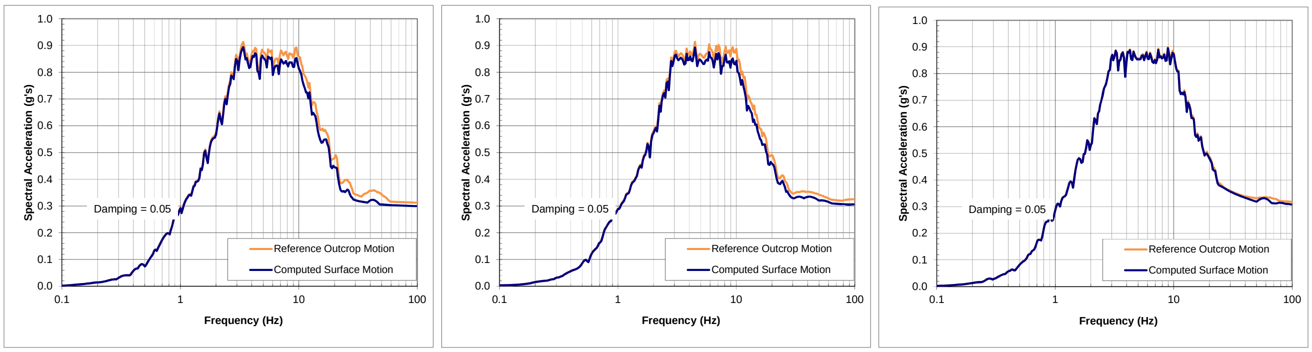

a) Acceleration Time Histories

b) Response Spectra

**Fig 8 – Acceleration Time Histories and Response Spectra of EUR-Medium Motion**

## SITE RESPONSE ANALYSIS

One-dimensional site response analysis was performed using SHAKE91 [4] to calculate free-field motions at the ground surface for use in the MTR/**SASSI** SSI model. The input motions applied to SHAKE91 consisted of reference motions specified as full-soil column (FSC) outcrop motions at the elevation corresponding to the base of the NI foundation. Because strain-compatible soil properties are assigned to generic soil profiles, no iterations of the soil properties were performed. A typical comparison of the response spectra of input motion specified at the soil outcrop, with calculated motions at the surface in the x-, y- and z-direction, is shown in Figure 9a, 9b and 9c, respectively. According to these results, the computed motions at the ground surface are similar to those of the soil outcrop motions at the NI foundation for the generic Soil Case 24n4u.




a) X-Direction b) Y-Direction c) Z-Direction

**Fig 9 – Comparison of Input and Calculated Spectra at Ground Surface**

## SEISMIC ANALYSIS RESULTS

The results of the lumped-mass stick and detailed FE models in terms of maximum accelerations, in-structure response spectra at key structural locations, and total interstory maximum forces and overturning moments are compared below.

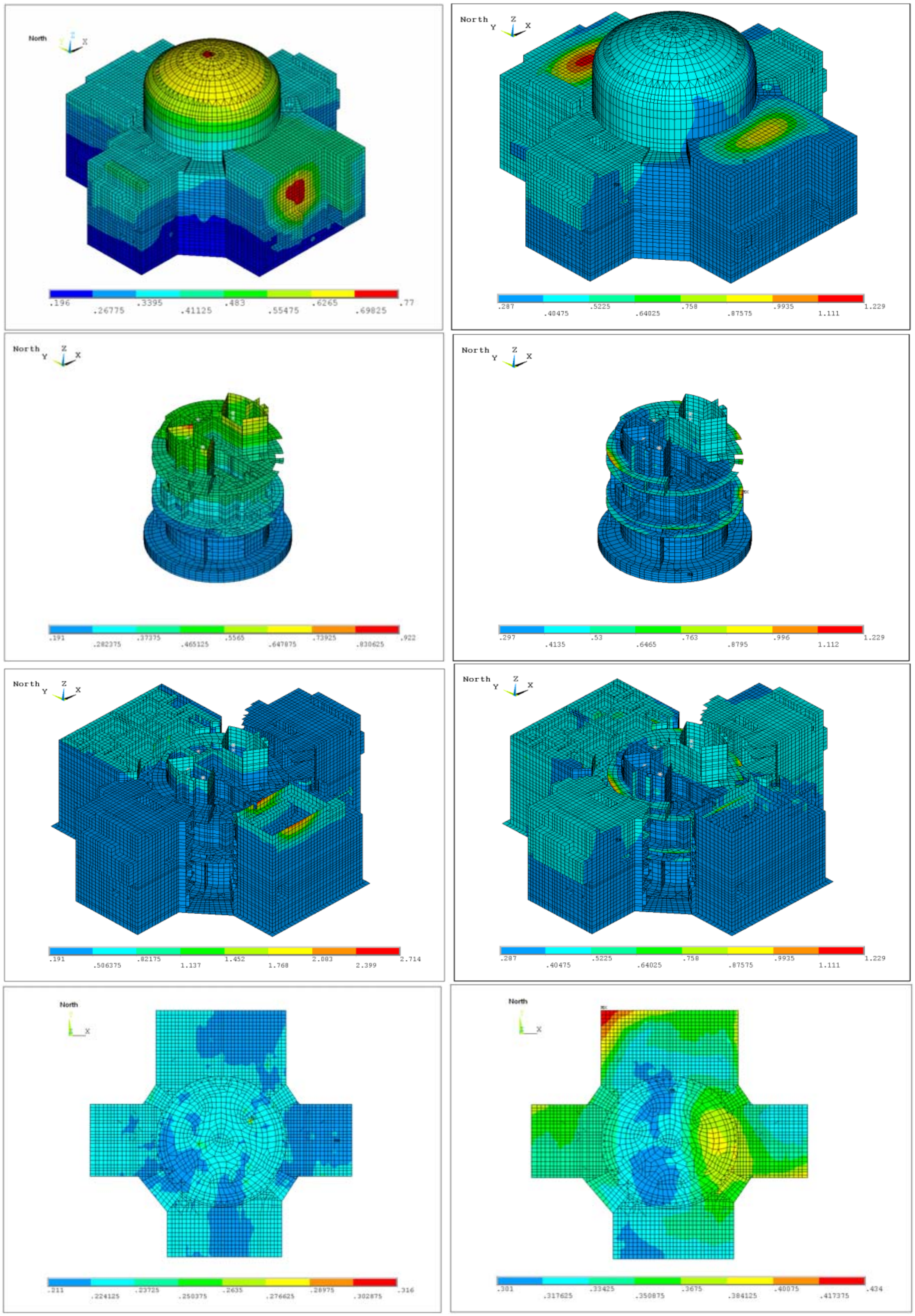
### Maximum Accelerations

The typical acceleration contours, calculated from detailed models of the RBIS, NI interior and exterior structures, and NI basemat in the y- and z-directions, are shown in Figures 10a and 10b, respectively. The accelerations, in general, show an increasing trend toward elevation except at the locations of flexible diaphragms.

At several key locations in the NI structures, maximum accelerations were calculated from stick and detailed model analyses, and the results compared in Table 1. Although the models could not be compared at exactly the same locations, in general they indicate similar results.

**Table 1 – Comparison of Maximum Accelerations - Stick Model vs. Detailed FE Model**

| Location | Stick Model | | | | Detailed FE Model | | | |
|---|---|---|---|---|---|---|---|---|
| | Elev. (m) | Maximum Accel. (g's) | | | Elev. (m) | Maximum Accel. (g's) | | |
| | | X | Y | Z | | X | Y | Z |
| Center of NI Common Basemat | -11.85 | 0.277 | 0.210 | 0.318 | -11.85 | 0.262 | 0.224 | 0.319 |
| Reactor Building Internal Structures (RBIS) | 5.15 | 0.347 | 0.258 | 0.341 | 5.15 | 0.379 | 0.320 | 0.374 |
| Reactor Building Internal Structures (RBIS) | 19.50 | 0.421 | 0.391 | 0.366 | 19.50 | 0.513 | 0.419 | 0.388 |
| Safeguard Building 1 (SB 1) | 29.30 | 0.564 | 0.502 | 0.501 | 21.0 | 0.478 | 0.356 | 0.399 |
| Safeguard Building 2/3 (SB 2/3) | 12.00 | 0.411 | 0.409 | 0.446 | 16.30 | 0.400 | 0.433 | 0.413 |
| Safeguard Building 4 (SB 4) | 29.30 | 0.580 | 0.621 | 0.556 | 21.0 | 0.340 | 0.335 | 0.394 |
| Fuel Building (FB) | 3.70 | 0.350 | 0.294 | 0.357 | 4.20 | 0.300 | 0.364 | 0.298 |
| Reactor Containment Building (RCB) | 58.00 | 0.738 | 0.620 | 0.893 | 58.00 | 0.869 | 0.734 | 0.516 |
| Reactor Shield Building (RSB) | 61.40 | 0.843 | 0.854 | 0.578 | 61.40 | 0.598 | 0.679 | 0.490 |

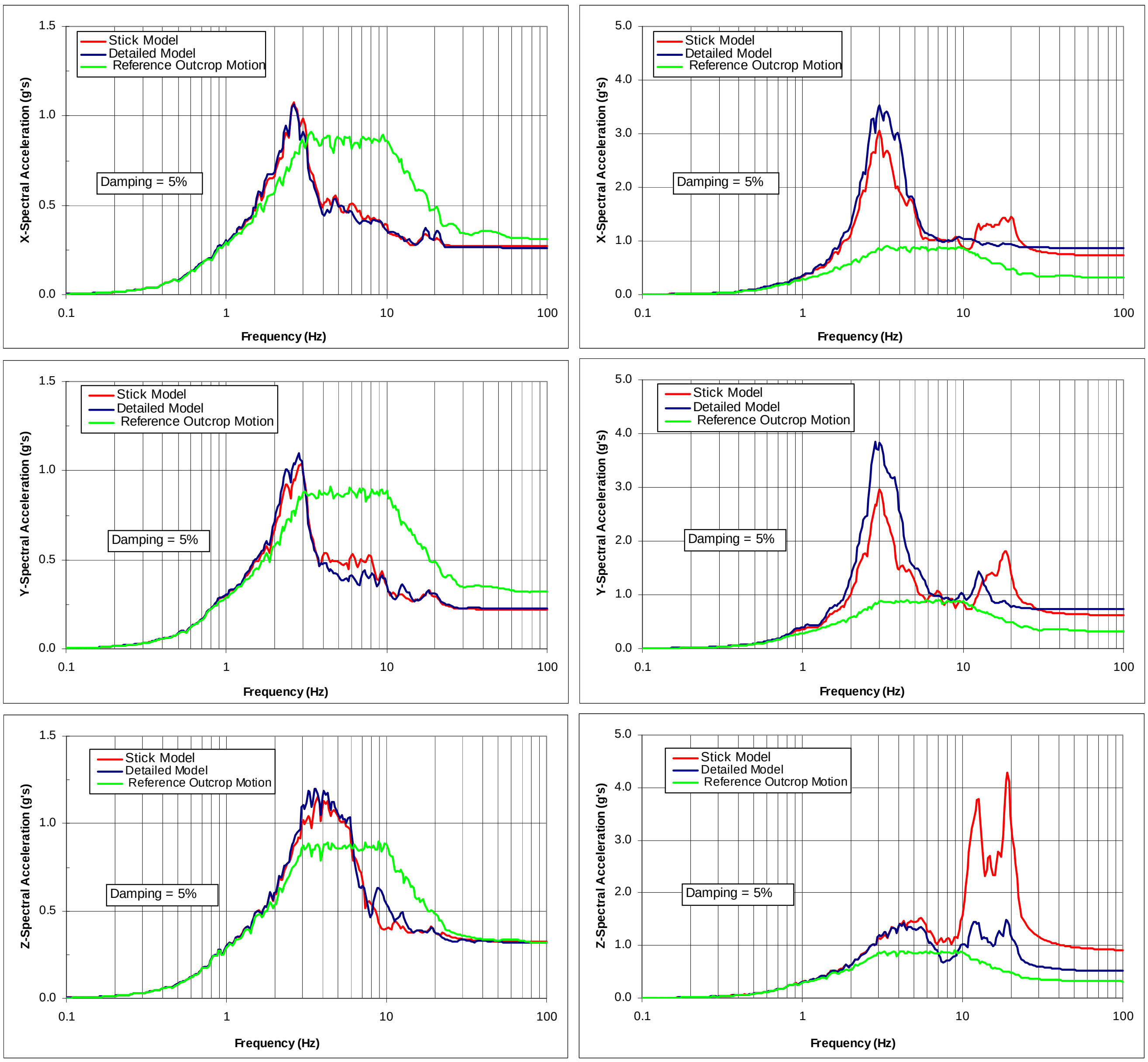


**a) Y-Direction** **b) Z-Direction**

**Fig 10 – Maximum Acceleration Contours of NI Structures**

## Acceleration Response Spectra

The acceleration response spectra computed at the center of NI basemat and top of Reactor Containment Building (RCB), together with the corresponding spectra of reference foundation outcrop motions in the same direction are shown in Figures 11a and 11b, respectively. The results show comparable responses from the stick and detailed models at the center of the NI basemat. However, the in-structure response spectra differ markedly despite an overall similarity in the spectral shapes. And at frequencies above 10 Hz, the stick model displays greatly amplified vertical spectral accelerations in the RCB, attributed to the differences in basemat rigidity between the two models. In general, stick models are capable of determining global seismic responses, but they can lead to excessively conservative results in the vertical direction due to the limited number of modes that can be modeled.




a) Center of NI Basemat (El. -11.85 m)

b) Top of RCB (El. 58.0 m)

**Fig 11 – Maximum Acceleration Contours of NI Structures**

### Interstory Forces and Overturning Moments

The maximum global dynamic interstory shear forces and overturning moments calculated from the stick and detailed models are compared in Figure 12. The results indicate close agreement between the two models.

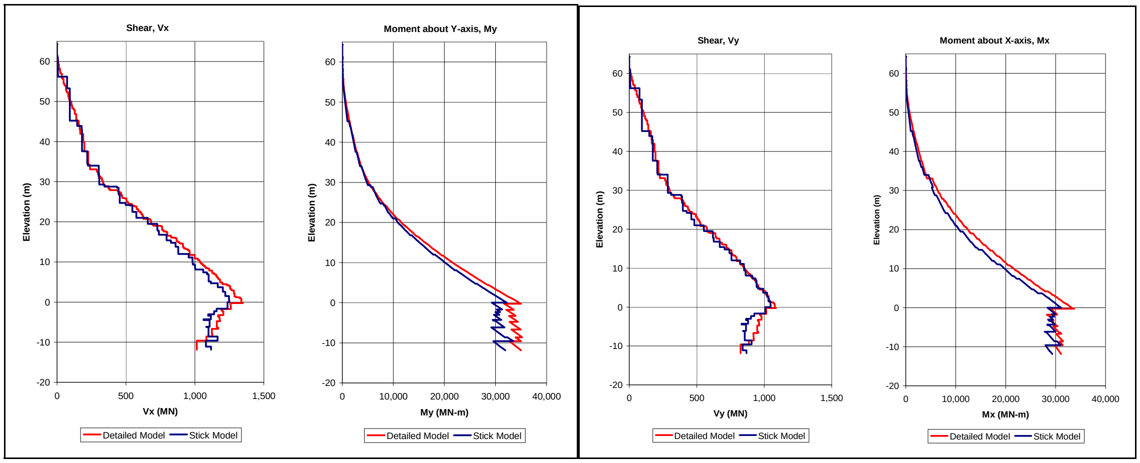



**Fig 12 – Maximum Absolute Total Interstory Forces and Overturning Moments**

## CONCLUSIONS

A 3-D detailed FE model of the US EPR™ Nuclear Island was developed and analyzed to evaluate the seismic SSI response using SASSI. The FE model consisted mainly of solid/shell elements representing concrete floors, walls and basemat. The NSSS, major equipment supports, and polar crane were included in the model using beam elements. The model considers spatial distributions of mass and stiffness in the structure, including the flexibility of the basemat, walls and floors. In addition, the model is made sufficiently refined to capture the out-of-plane flexural response of floors and walls.

The results of the detailed model at key locations in the structure have been computed and compared with those of a comparable lumped-mass stick model typically used in SSI analysis. The comparisons indicate a generally close agreement between the calculated global responses, such as maximum accelerations at major floor elevations, and interstory forces and moments. However, in terms of the calculated in-structure response spectra, the results of the two models differ markedly despite an overall similarity in spectral shapes. The differences in the spectral responses are more pronounced at higher elevations compared to the basemat level. This may be attributed to the flexibility of the floors, walls and basemat; the spatial distribution of mass in the structure (both of which are ignored); and the limited number of modes that can be represented by the stick model.

### Summary of Major Observations

- The detailed model captures local responses, thus eliminating the need for SDOF oscillators.
- Effects of the basemat flexibilities can be considered in detailed models.
- Meshing can be made sufficiently small in detailed models to capture the response from high frequency input motions.
- Stick models are capable of determining global seismic responses, but they can lead to excessively conservative results in the vertical direction due to the limited number of modes that can be modeled.

## REFERENCES

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