# SEISMIC SSSI OF A DEEPLY EMBEDDED SMR AND A BUILDING WITH DEEP FOUNDATION

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## Introduction

The paper presents a case study on the seismic structure-soil-structure interaction (SSSI) effects of an Annex Building (AB), supported by a deep pile foundation, on the seismic response of a typical, deeply embedded Small Modular Reactor (SMR) structure. Both structures are located at a shallow bedrock site comprising an approximately 80 ft thick layer of relatively soft soil overlying a hard bedrock. The SMR foundation extends below the bedrock surface. Due to insufficient bearing capacity of the upper soil layers, piles are installed beneath the AB to transfer vertical building loads to the underlying bedrock. This paper investigates the SSSI effects of the AB's pile foundation on the seismic response of the deeply embedded SMR, with a focus on in-structure responses and the seismic stress demands on the SMR's exterior wall.

The effects of the AB deep foundation on the SMR's seismic response are evaluated by comparing results from SSSI analyses of combined SMR-AB models that incorporate two different AB foundation types: (1) a deep foundation with piles and (2) a surface-mounted foundation. These SSSI results are further compared with the results from standalone soil-structure interaction (SSI) analysis of the SMR to assess the overall influence of SSSI. Additionally, the influence of wall-soil interface stiffness conditions on the SMR's response is evaluated by comparing results from bounding cases of SSSI models with different soil-wall interface assumptions.

## CASE STUDY

The SSSI effects from adjacent AB structure on the seismic response of deeply embedded SMR structure are investigated considering typical shallow rock site conditions represented by generic profile 500-21 defined in Section 7 of NEDO 33914-A (2021) and Todorovski at al. (2022). The 500-21 generic profile includes an approximately 80 ft deep layer of relatively soft granular soil materials resting on a hard bedrock stratum. Figure 1 shows shear wave velocity (Vs) and compression wave velocity (Vp) profiles defining the variation of soil and rock stiffness properties at the 500-21generic shallow rock site.

The study uses coherent input ground motions with amplitude and frequency content that are defined by the Median Generic Design Response Spectra (GDRS) presented in NEDO-33914A (2022). Figure 2 presents the 5% damped GDRS that define the horizontal components of the seismic motion at the site ground surface elevation. In-column soil control motions compatible to these Median GDRS were applied to the SSI analysis model at the SMR foundation level.

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The study is focused on the seismic response of a SMR structure that has a square footprint with dimensions of 100ft by 100ft and a total height of 162.5 ft of which 118 ft are embedded in soil and rock. The adjacent AB has footprint dimensions of 200 ft x 85 ft and hight of 130 ft and is supported by reinforced concrete basemat resting on the nominal ground elevation. It is separated from the SMR by a 2.5 ft gap. Figure 3 shows the considered general layout of the SMR and AB.

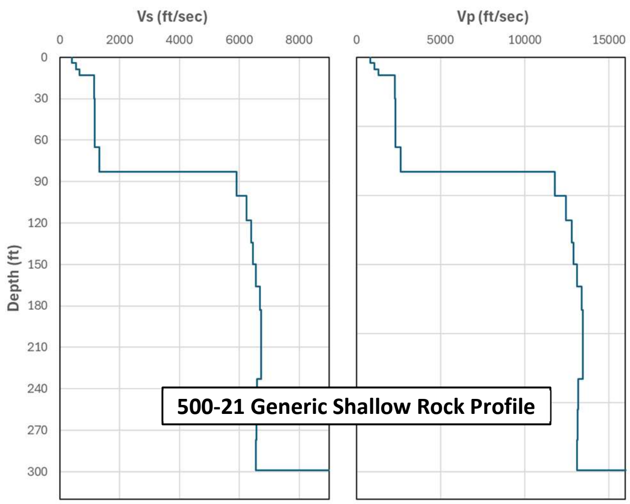


Figure 1 Shallow Rock Site Subgrade Profile

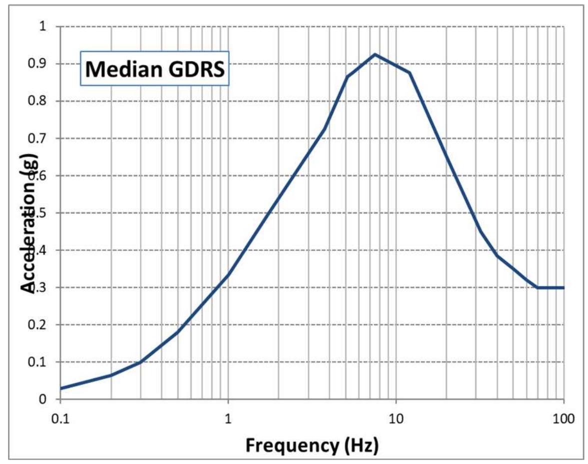


Figure 2 Horizontal Median GDRS

The SMR exterior and containment reinforced concrete walls are 3 ft thick, and the other interior reinforced concrete shear walls are 2 ft thick. The total dynamic weight of the deeply embedded SMR is 240,000 kips resulting in an equivalent uniform base pressure of 24ksf. The weight of the AB is 200.000 kips, which is 83% of the SMR weight, resulting in an equivalent uniform foundation bearing demand of about 12.5 ksf. The soil bearing capacity at this site may not be sufficient to support this bearing pressure demand, therefore, a deep foundation may be needed to transfer the weight of the AB to the bedrock.

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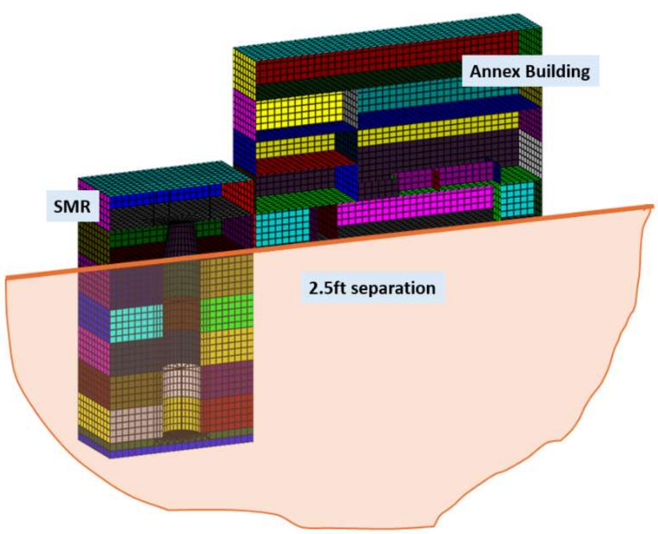



Figure 3 Deeply Embedded SMR and AB Layout

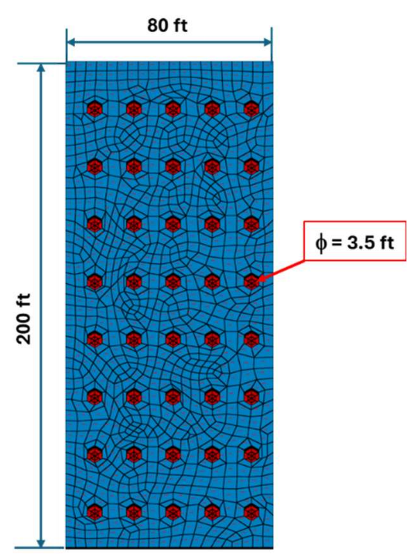



Figure 4 AB Deep Foundation Configuration

To investigate the effects of deep foundation elements on the seismic response of the adjacent SMR, the study considers a deep foundation configuration where the AB basemat is supported by a total of 40 reinforced concrete piles. Figure 4 presents the configuration of the AB pile foundation. Each pile has a diameter of 3.5 ft and a length of 87. 2 ft, with the pile cap socketed 4.4 ft in the underlying rock formation.

Figure 5 presents the combined SSSI analysis finite element (FE) model of the deeply embedded SMR and the AB with its pile foundation. The global coordinate system of the FE model is defined with the origin at the SMR centreline at ground level. The positive z-axis is oriented upwards, and the positive x-axis points toward the adjacent AB. Thick shell elements represent the dynamic properties of the SMR and AB reinforced concrete walls, slabs, roofs and basemats. The excavated soil and the piles are modelled using 3-D solid elements. The fixed base natural frequency of vibration of the SMR in the horizontal direction is 4.3 Hz. The horizontal frequencies of the AB fixed at the basemat elevation in the horizontal x and y directions are 5.5 Hz and 3.8 Hz, respectively.

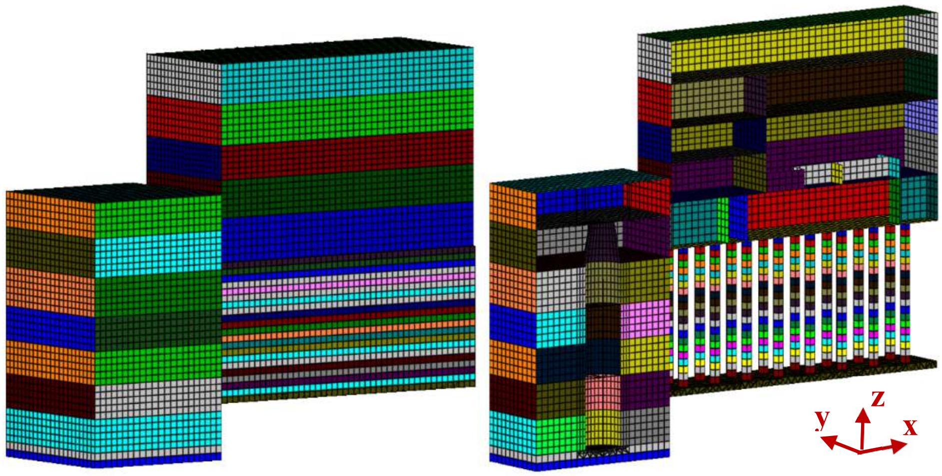



Figure 5 Combined FE Model of Deeply Embedded SMR , AB and AB Pile Foundation

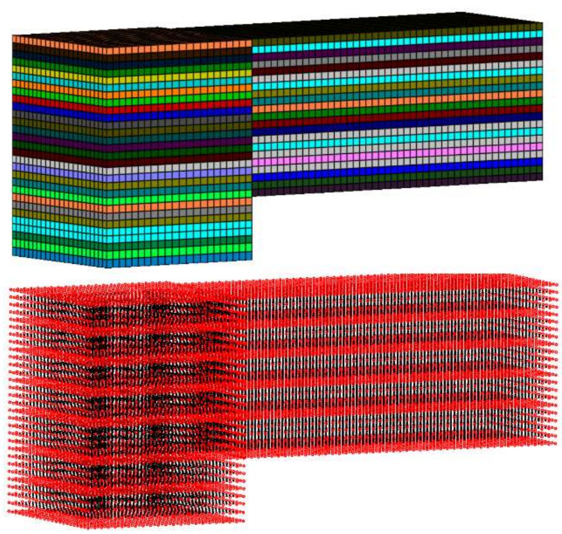


Figure 6 Excavated Volume Intyeraction Nodes

Frequency domain SSI analyses were performed using the ACS SASSI Fast Flexible Volume (FFV) approach (GP Technologies, 2023), which is a special case of the Extended Subtraction Method (ESM). The Flexible Volume Reduced-Order Modelling with Impedance Interpolation (FVROM-INT), described in (Ghiocel and Todorovski, 2024) and (Hashemi et al., 2024,) was implemented for these analyses for obtaining fast SSI solutions. As shown on Figure 6, interaction nodes were set at all nodes of the excavated volume outer surfaces plus additional 6 and 4 layers of internal nodes at the SMR and AB portions of the excavated volume, respectively. The total number of excavated volume and FFV interaction nodes are 37,584 and 14,202, respectively.

The effects of the AB pile foundation on the SMR seismic response were investigated by comparing results of SSSI analyses performed on the combined SMR-AB model with AB pile foundation and the combined SMR-AB model with AB shallow surface mounted foundation. Comparisons were also made with the results of SSI analyses of the SMR standalone model. The AB basemat was disconnected from the underlaying soil in the combined deep foundation SSSI model to consider the AB interaction with the site only through the stiffer pile elements,

Two sets of SSSI analyses were performed to address the modelling of conditions at the SMR wall-soil interfaces on the SMR SSSI responses. Similar to the approach implemented in the study presented elsewhere (Ghiocel and Todorovski,2025), these effects were evaluated by comparing the SSSI responses obtained from the model with fully bonded wall-soil interfaces with those calculated from the analyses of a model representing the bounding condition of no-friction smooth wall-soil interfaces.

## Effects of Pile Foundations on SMR Sesimic Response

The effects of the AB pile foundation on the seismic response of the deeply embedded SMR structure are investigated by comparing 5% damped in-structure response spectra (ISRS) for the response at two key nodal locations shown in Figure 7. To illustrate the effects of the AB pile foundation on the SMR structure stress response, comparisons are made of diagrams presenting the amplitude and distribution of the in-plane shear, out-of-plane shear and vertical axial forces acting along the height of the exterior wall facing the AB. Figure 8 shows the SMR wall shell elements along the wall vertical midline used for the comparisons of structural stress demands.

Figures 9 through 12 present comparisons of results from the different seismic analyses. The results of the SSSI analyses of the combined model of the SMR and AB with a pile foundation are shown in red. The results of the SSSI analyses of the combined model of the SMR and AB with a shallow surface mounted foundation are shown in green. The ISRS for the SMR standalone SSI responses are shown in black. Results obtained from the analyses of models with fully bonded interfaced conditions are shown with solid lines, and results obtained from models with smooth no-friction SMR wall soil interfaces are shown with dashed lines.

The three left plots in Figure 9 compare ISRS for the response of Node 11543 with coordinates X = 50 ft, Y = 50 ft and Z = 0 ft that is located at the ground level elevation at the corner of the SMR exterior wall facing the adjacent AB. The right set of plots in Figure 9 show ISRS for the responses of Node 13199 with coordinates X = 50 ft, Y = 50 ft and Z = 44.5 ft located at the SMR roof corner that is next to the adjacent AB. The ISRS for responses in the horizontal (X) direction towards the adjacent AB at these two locations are presented in the top two plots. The plots in the middle show the ISRS for the responses in the other horizontal (Y) direction. The bottom plots show the vertical (Z) direction ISRS.

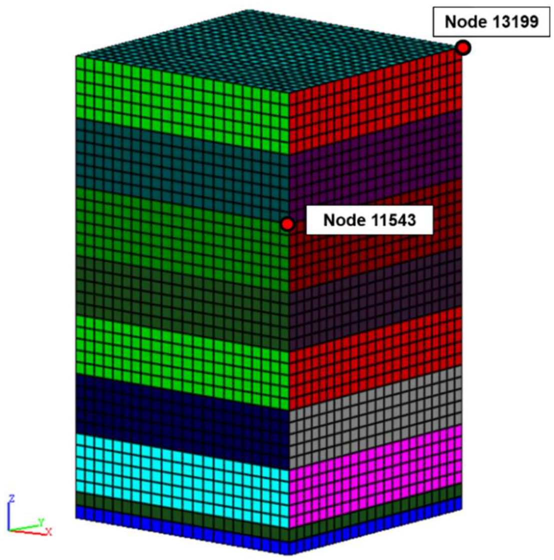



Figure 7 ISRS Key Nodal Locations

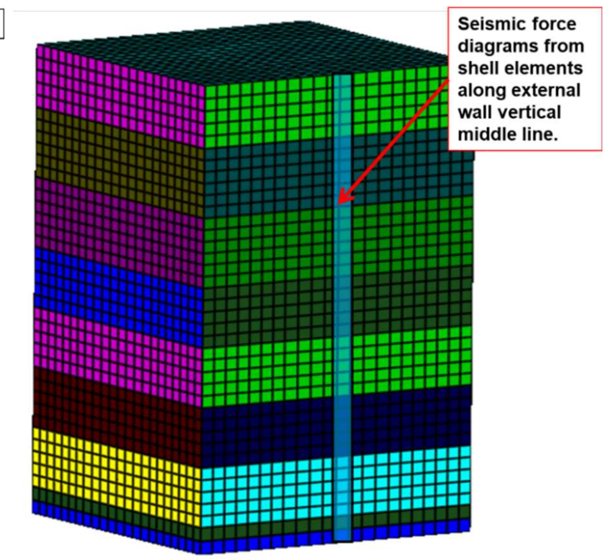



Figure 8 Internal Force Diagrams Location

The comparisons in Figure 9 indicate that the piles installed below the adjacent AB reduce the SSSI effects on the response of the deeply embedded SMR. The ISRS obtained from the SSSI analysis of combined model with pile foundations (red lines) are close to those calculated from the SMR standalone SSI analysis (black lines). The results indicate only small SSSI induced peak response amplifications which for the considered pile configuration are basically insignificant. No significant peak frequency shifts can be observed in the SSSI responses of the deeply embedded SMR when the AB is supported by the deep pile foundation. On the other hand, the effects of SSSI can result in frequency shifts in the horizontal ISRS peaks when the AB is supported only by a surface foundation (green lines). The most pronounced SSSI effects are observed for the response in the horizontal X-direction towards the adjacent AB. The SSSI effects in the other horizontal Y-direction and the vertical Z-directions are less significant.

A previous separate study of SSSI effects (Ghiocel and Todorovski,2025) indicated that the modelling of the SMR wall-soil interfaces may have significant effect on the calculated SSSI responses of the deeply embedded SMRs. Figure 10 illustrates how the stiffness of SMR wall-soil interfaces affected ISRS results of this study by comparing ISRS obtained from the SSSI analysis of the model with fully bonded interface conditions (solid lines) with ISRS obtained from a model with smooth no-friction SMR wall-soil interfaces (dashed lines). These presented ISRS are for the SMR response of the corner Node 11543 located at ground elevation, where the SSSI effects are the most pronounced. The left plot compares the ISRS for the SMR response in the horizontal X-direction, and the right plot shows comparisons of ISRS responses in the vertical direction.

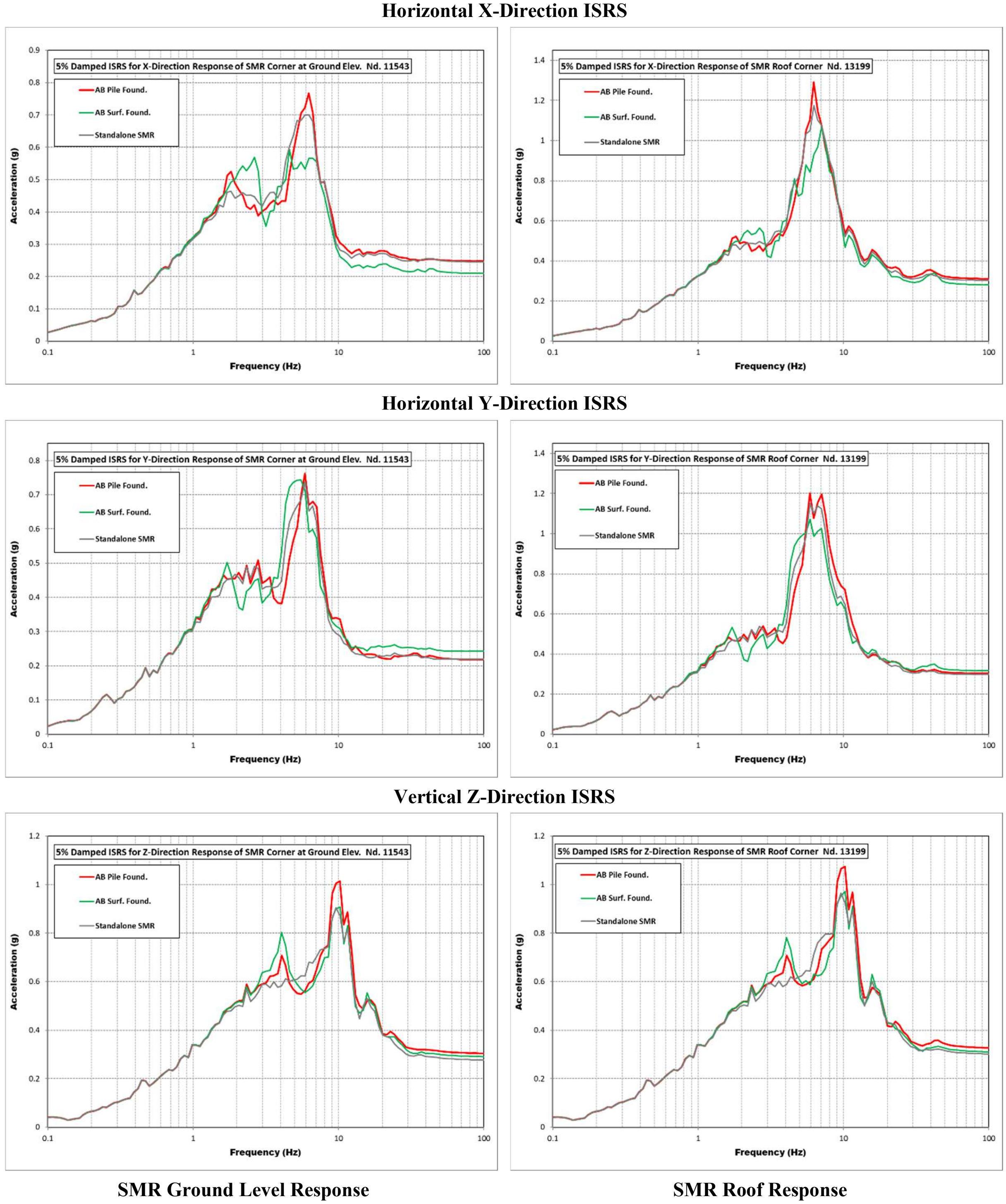
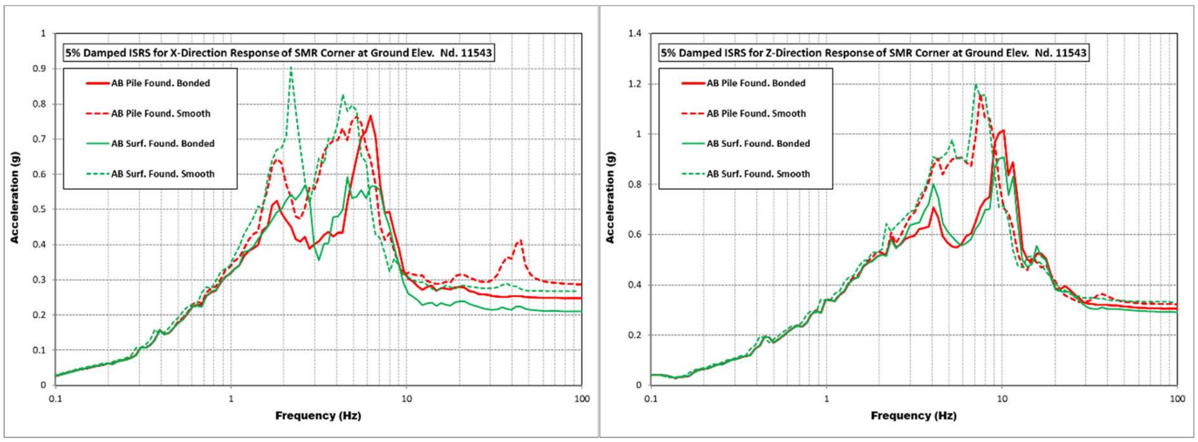



Figure 9 SSSI Effects of Different AB Foundation Types on SMR ISRS

The comparisons in Figure 10 show that the modeling of wall-soil interface stiffness can have a significant effect on the SSSI response of the deeply embedded SMR, as it was also noted in the previous study (Ghiocel and Todorovski, 2025) that investigated the SSI effects of a partially embedded AB on the sesimic response of the deeply embedded SMR. These modeling effects can be more pronaunced when the AB is supported by a deep pile foundation, resulting in signifcantly higher peak in-structure responses in the horizontal X-direction than those observed when the AB has a surface mounted foundation. Overall, the comparisons in Figure 10 suggest that the effects of modeling of the wall-soil interface conditions on the in-strucutre response of the deeply embedded SMR may be far more significant than the type of foundation used to support the AB.




**Horizontal X-Direction ISRS** **Vertical Z-Direction ISRS**

Figure 10 Effects of Modeling Wall-Soil Interface Conditions on SMR SSSI response

Figures 11 presents diagrams of the in-plane shear, out-of-plane shear and vertical axial forces acting on the SMR external wall along its vertical midline (Figure 8). The plots indicate that the SSSI effects with the adjacent AB amplify the seismic stress demands on the SMR extiror wall by showing that the standalone SSI analyses (black lines) yielded lower element force results than the two SSSI analyses. These SSSI induced amplifications are the most pronaunced for the out-of-plane shear demands presented in the middle plot of Figure 11, and are relatively insignificant for the in-plane shear demands presented in the left plot.

The comparisons of in-plane shear and axial foce diagrams calculated from ther SSSI analyses results indicated that the introduction of piles under the AB basemat in general reduce the in-plane shear and the vertical axial force demands on the SMR exterior wall. On the other hand, the piles can affect the distribution of the out-of-plane shear demands on the wall by transfering the AB loads from the surface mounted basemat deeper in the soil. The redistribition of these loads can result in higer out-of-plane shear demands on the SMR exterior wall.

The SMR wall demands presented in Figure 11 are obtained from the analyses of models with fully bonded SMR wall-soil interfaces. In order to illustrate the effect of modeling the wall-soil interfaces on the calculated diagrams of SMR wall force demands, Figures 12 compares the results obtained from the SSSI analyses of the model with fully bonded SMR wall-soil interfaces (solid lines) with those calculated from the model representing smooth, no friction, wall-soil interface conditions (dashed lines).

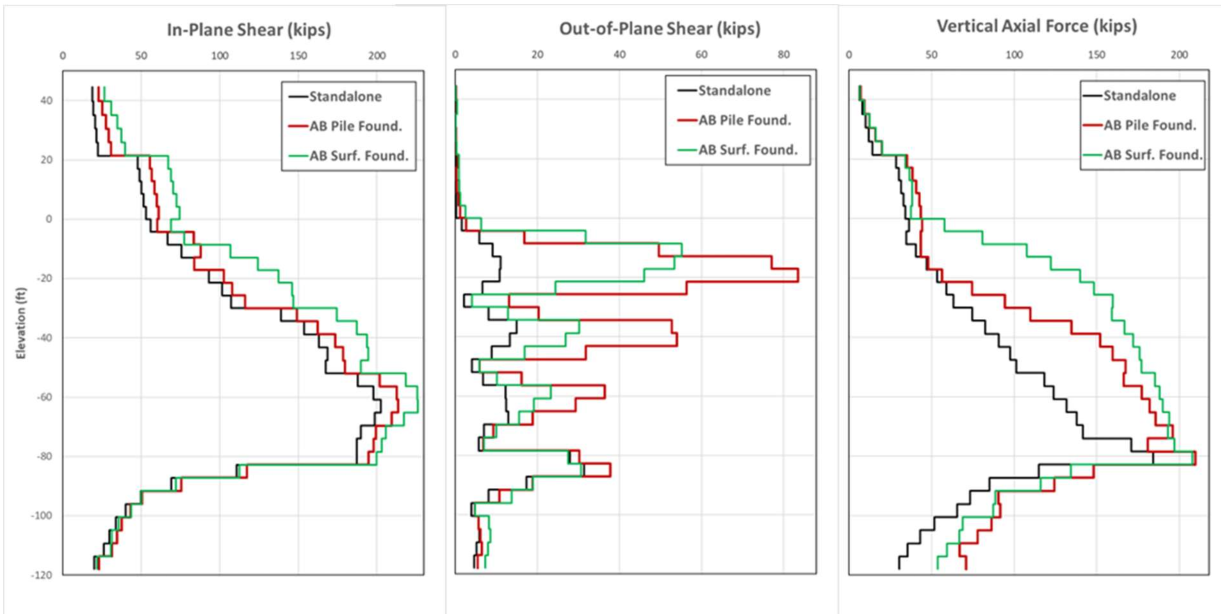



Figure 11 SSSI Effects of Different AB Foundation Types on SMR Wall Stress Demands

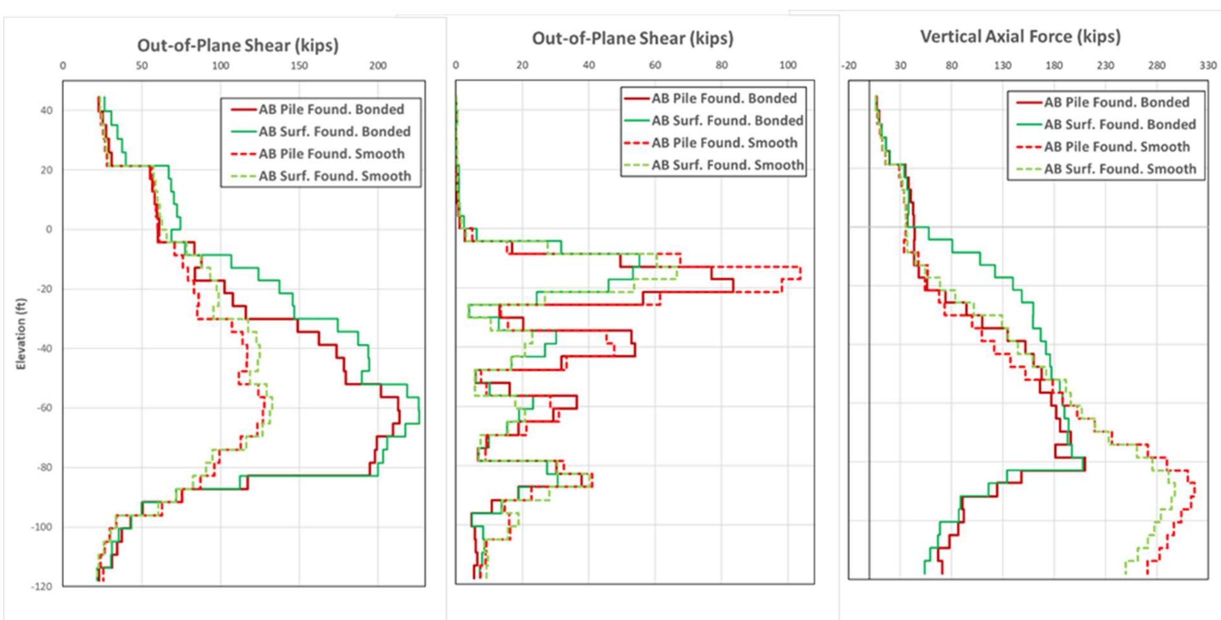



Figure 12 Effects of Modeling Wall-Soil Interface Conditions on SMR Wall Stress Demands

The comparisons in Figure 12 indicated that as noted in previous study (Ghiocel and Todorovski, 2025), the modeling of wall-soil interface stiffness can significantly affect the calculations of the sesimic demands used for the design the deeply embedded SMR exterior wall. The first plot in Figure 12 shows that the reduced friction stiffness of the wall-soil interface reduces the in-plane shear demand on this wall. On the other hand, the smooth interface conditions can significantly amplify the out-of-plane shear demands on the wall as shown by the plot in the middle of Figure 12. As shown in the right plot of Figure 12, the friction conditions at the wall-soil interface significantly affect both the amplitude and distribution of the axial forces in the wall.

## Conclusions

This paper presents a case study on SSSI effects of an AB supported by deep pile foundation on the seismic response of a deeply embedded SMR. The study is based on comparison of results from several SSSI analyses of models representing different AB foundation types and a SSI analysis of a standalone SMR model. The main conclusions are as follows:

- Installing piles beneath the AB foundation reduced the SSSI effects on the in-structure seismic responses of the deeply embedded SMR. ISRS obtained from the SSSI analyses with the pile-supported AB were very similar to those from the standalone SMR SSI analysis. In contrast, ISRS from SSSI analyses involving surface-supported AB foundations showed notable frequency shifts and amplifications of SMR peak responses.
- The presence of the adjacent AB amplified seismic stress demands on the SMR below grade walls. The standalone SSI analyses yielded lower element force results compared to the SSSI analyses. The comparisons of sesimic demand indicated that, for the studied configuration, SSSI induced amplifications were significant for the out-of-plane shear demands, while in-plane shear demands were relatively unaffected..
- Piles beneath the AB basemat reduced the in-plane shear and the vertical axial force demands on the SMR exterior wall. However, they altered the distribution of the out-of-plane shear demands by transfering the AB loads from the surface mounted basemat deeper into the soil. For the configuration studied, this resulted in higer out-of-plane shear demands on the portion of the SMR exterior wall that is adjacent to the piles.
- Wall-soil interface stiffness significantly impacts computed SSSI responses. The reduced friction stiffness of the wall-soil interface lowered the in-plane shear demans but increased the out-of-plane shear demands on the SMR exterior wall. Comparisons between results obtained from fully bonded and smooth wall-soil interface models indicated thatthese interface conditions can influence ISRS results more than the choice between surface or pile-supported AB foundations.
- The impact of wall-soil interface friction on in-structure SMR responses is more pronounced when the AB is supported by deep foundations. The SSSI analysis results revealed that the use of bounding smooth interface conditions produced significantly larger amplifications of both horizontal ISRS peak responses and wall out-of-plane shear forces when the AB is supported by the deep pile foundation.

These conclusions are based on a case study involving specific site conditions, building layout, and pile foundation configuration. While they provide general guidelines for the importance of the SSSI effects of deep foundations on the seismic response of deeply embedded SMRs, actual SSSI responses may vary depending on the specific site characteristics, plant layout, and design of the SMR and its foundations.

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