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GENERIC DESIGN OF DEEPLY EMBEDDED SMALL MODULAR REACTORS

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ABSTRACT

Deeply embedded Small Modular Reactors (SMRs) provide a safe and economical design solution by having most of the safety-important equipment, systems and components located below grade. The surrounding subgrade helps protect the below-grade portion of the SMR from external loads, and in general, also helps reduce the seismic response and demands on the SMR structure and the safety-important equipment, systems, and components. An embedded structure with a cylindrical shape design enables most of the resistance to lateral earth pressure loads to be provided by the compressive strength of the external shaft wall. This paper presents results of standard design static and seismic Soil-Structure Interaction (SSI) analyses of a typical SMR structure, which is deeply embedded in in-situ soil and rock. Using a one-step approach, static and seismic SSI analyses are performed on a refined Finite Element (FE) model for a set of generic profiles of static and dynamic subgrade properties and Certified Seismic Design Response Spectra (CSDRS) representative of a wide range of geotechnical and seismological conditions present at candidate sites for deployment of SMRs. Results of the SSI analyses for different types of geotechnical and seismic site conditions are compared to evaluate their effects on the design of the deeply embedded SMR structure.

ONE-STEP APPROACH SSI ANALYSIS

The interaction of the deeply embedded SMR structure with the surrounding soil and rock is an important factor for structural integrity of the SMR and the safety of the plant. The surrounding subgrade exerts static earth pressure loads on the SMR structure due to its weight and surcharge loads from foundations of buildings and equipment located in the vicinity of the deeply embedded SMR structure. The SMR structure is also subjected to additional dynamic earth pressure loads when subjected to earthquake ground shaking, including dynamic earth pressures due to structure-soil-structure interaction (SSSI) with adjacent structures and foundations. The kinematic interaction of the deeply embedded SMR structure with the surrounding in-situ soil and rock are critical for the seismic response and design of the safety-important SMR structures, systems, and components (SSC). The interaction of the deeply embedded SMR structures with the surrounding in-situ soil and rock determines the magnitude and distribution of the static and dynamic earth pressure loads as well as the boundary conditions at the interface with surrounding soil and rock; thus, affecting both the SMR structural response and the distribution of stress in the SMR structure.

The one-step approach is implemented for the structural design to adequately account for the interaction of the deeply embedded SMR structure with the subgrade (NEDO-33914, 2022). Demands on the SMR structural members due to static and dynamic earth pressure, dead loads and seismic inertia loads are obtained directly from the results of static and seismic SSI analyses of the linear elastic FE model. The SASSI (A System for Analysis of Soil Structure Interaction) sub-structuring method is implemented for the

SSI analyses of gravity and seismic inertia loads, including the static and dynamic earth pressure loads, applied to the structure from the surrounding subgrade. The SSI system is subdivided into three substructures:

- a structural model representing the deeply embedded SMR structure and surrounding building foundations;
- an excavated volume model representing the properties of excavated subgrade materials replaced by the embedded part of the SMR structure; and
- a far-field subgrade model representing the properties of the soil and rock materials

The results of different sub-analyses are combined using the principle of superposition to obtain the final solution for the response of the SSI system under the seismic and gravity accelerations.

The analyses presented in this paper are performed on the FE model of a typical cylindrical SMR structure, shown in Figure 1, with a diameter of 34 m and a total height of approximately 60 m, of which more than half (35 m) is embedded. The structural FE model consists of shell elements representing the SMR outer shaft cylinder, inner shaft cylinder, wing shear walls, slabs and basemat that are constructed using steel-plate composite (SC) modules. The properties of the shells used to represent these SC members are estimated in accordance with AISC N690-18. The dynamic properties of the Reactor Pressure Vessel (RPV) and its internals are represented by beams, springs, and lumped mass elements. The roof of the SMR structure is modelled using beams and shell elements. Shell elements are added on the surface of the subgrade model at the footprint of the other surrounding power block buildings to account for the overburden pressures on the deeply embedded SMR.

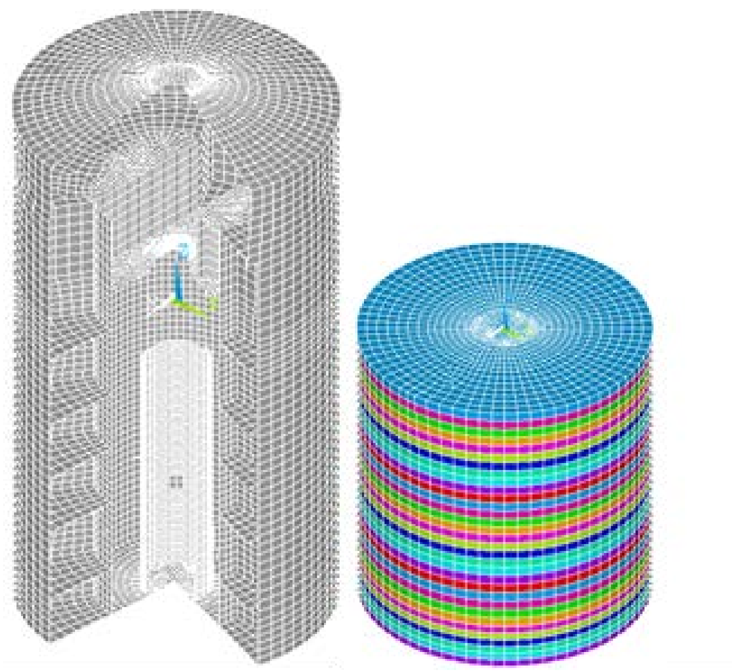

Figure 1. One-Step Approach SMR and Excavated Volume FE Model

The far-field subgrade is represented by a layered half-space continuum with equivalent linear properties developed as described in Todorovski, et al. (2022). As shown in Figure 1, solid elements represent the properties of the excavated subgrade materials. Fully bonded conditions at the soil-structure interface are considered to maximize the effect of the subgrade conditions on the SMR structure response and design.

EFFECTS OF SUBGRADE CONDITIONS ON STATIC DESIGN DEMANDS

Table 1 provides a list of static SSI analyses performed on a set of seven generic profiles of in-situ subgrade static properties provided in Todorovski, et al. (2022). The profiles are defined in terms of average measured shear wave velocity of the top 30 meters of soil ($\bar{V}s_{30}$) and the depths to the geological base rock. The generic profiles provide a realistic representation of a wide range of geotechnical conditions present at sites that are suitable for deployment of SMRs. Soil sites are represented by profiles 180-600, 270-60, 400-300, and 500-21 for which the SMR structure is embedded in medium stiff soil and rock. Profiles 760-60, 760-15 and 900-8 represent soft and firm rock sites. Hard rock conditions represented by profile 2032-30 are not considered since the static earth pressures from sound hard rock are minimal.

Table 1: Matrix of Generic Static SSI Analyses

Analysis Case No.	Subgrade Profile	Max. Hoop Membrane Force (kip/ft)	Description
1	180-600	-214	Deep medium stiff soil site
2	270-60	-205	Firm soil site
3	400-300	-184	Deep stiff soil site
4	500-21	-115	Shallow medium stiff soil site
5	760-60	-179	Deeper soft rock site
6	760-15	-110	Shallow soft rock site
7	900-8	-119	Firm rock site

The response of the deeply embedded SMR structure under gravity and earth pressure loads is calculated from equivalent static SASSI analyses. Maximum dynamic responses of the SSI system that are equivalent to its static response under 1-g gravity load are calculated by applying an equivalent static 1-g excitation in the vertical direction as vertically propagating compression waves. To simulate the 1-g static excitation, a very low frequency harmonic acceleration time history is used with an amplitude equal to Earth's gravity (g). The 1-g excitation is applied to the SASSI model at a control point located at the surface of the site free-field model. The equivalent static SASSI analysis is performed for a few frequency points only. Maximum acceleration results of the 1-g SSI analysis at selected node locations are inspected to ensure the maximum gravity load of 1-g is applied uniformly throughout the SSI model.

Table 1 lists the maximum hoop membrane forces in the below-grade outer shaft wall calculated from the static SSI analyses of the seven subgrade profiles to illustrate the effects of different site subgrade conditions on the design of the deeply embedded SMR structure. The hoop membrane forces are present in units of 1 kip per 1 ft of wall length, where 1 kip/ft = 14.6 kN/m. The effect of the subgrade conditions on the design of the deeply embedded SMR are best shown by the hoop stresses in the below-grade wall that are primarily caused by the external earth pressure and surcharge load from adjacent buildings. The comparison of the maximum stress results in Table 1 show that soil profiles provide the largest hoop stresses. The outer shaft hoop stresses obtained from the analysis of the deep medium stiff soil profile 180-600 are almost double when compared to those obtained from the analyses of the firm rock profile 900-8, exhibiting close to half of the maximum stress for the softest profile case.

A range of the observed hoop stress responses are illustrated in Figure 2 that presents the distributions of hoop stresses in the below-grade outer shaft wall for four of the seven analysed subgrade profiles.

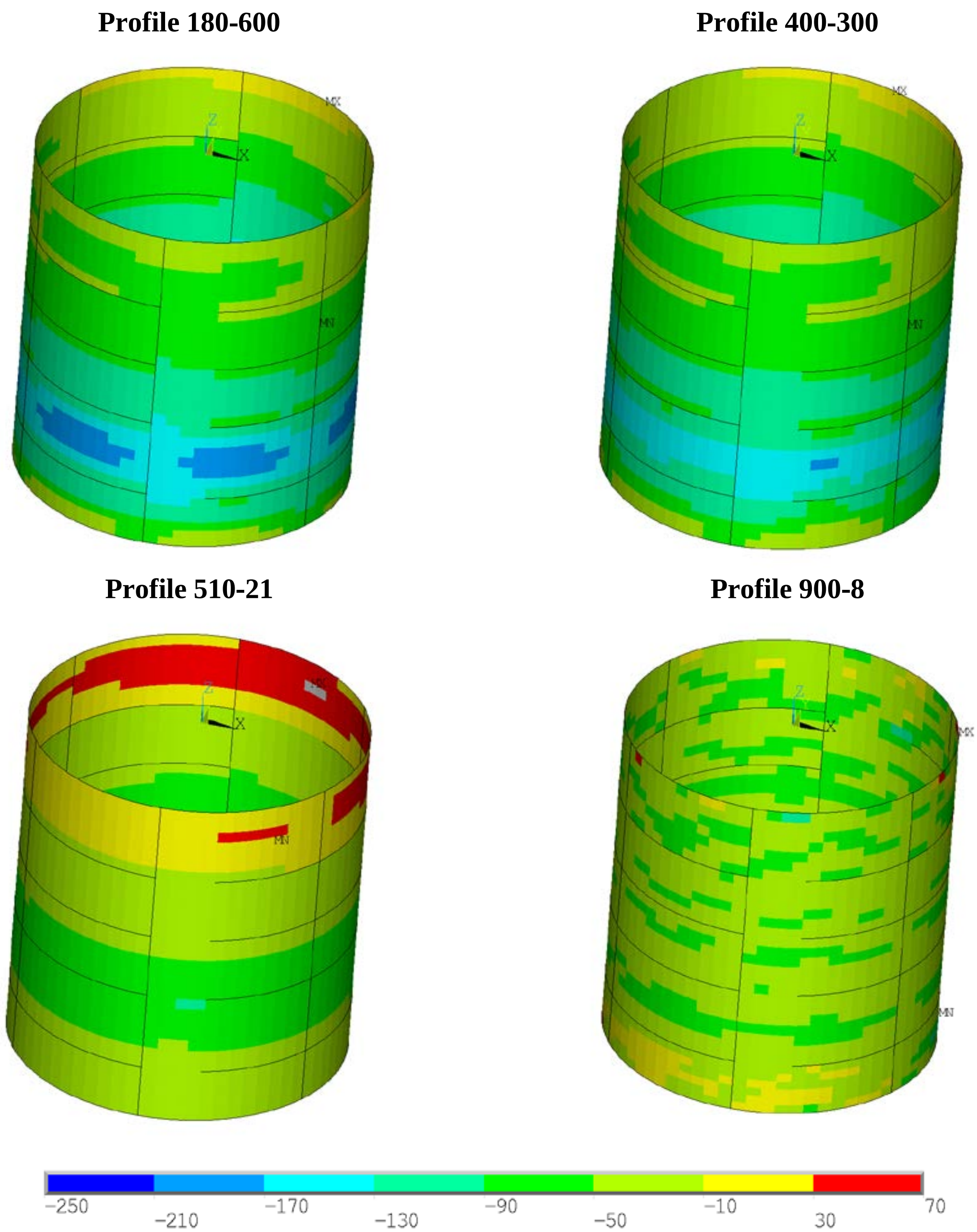

Figure 2. Hoop stresses for the Static SSI cases in the outer shaft wall below grade (kip/ft)

EFFECTS OF SUBGRADE CONDITIONS ON SEISMIC DESIGN DEMANDS

Results obtained from eleven sets of generic seismic SSI analyses, listed in Table 2, are used to evaluate the effects of different types of seismological and geotechnical site conditions on the seismic response and design of the deeply embedded SMR structure. The seismic SSI analyses are performed for eight generic profiles of dynamic subgrade properties provided in Todorovski, et al. (2022). Three sets of horizontal and vertical CSDRS, shown in Figure 3, define the design motion at ground surface. These CSDRS were developed in Todorovski, et al. (2013) to accommodate the seismic conditions at a wide range of sites.

Table 2: Matrix of Generic Seismic SSI Analyses

Analysis Case No.	Subgrade Profile	CSDRS	Max. Vertical Axial Force (kip/ft)	Max. In-Plane Shear Force (kip/ft)
1	180-600	Firm	108	230
2	270-60		75	190
3	760-15		98	56
4	400-300	Median	67	97
5	500-21		84	102
6	760-15		117	85
7	900-8		113	90
8	500-21	Hard	53	65
9	760-60		71	51
10	900-8		82	58
11	2032-30		101	53

The input free-field control motion is applied to the SSI model at the bottom of the SMR foundation as vertically propagating shear and compression waves in the two horizontal directions, and vertically propagating compression waves in the vertical direction. Eleven sets of two horizontal and one vertical control motion acceleration time histories (ATHs) were developed by spectral fitting a set of three recorded ground motion seed time histories to the horizontal and vertical target spectra representing the outcrop CSDRS defined ground motion at the bottom of the deeply embedded SMR structure. These spectrum-compatible outcrop motion ATHs were converted to in-column motion ATHs for use as input for the SSI analyses. The responses due to the three components of the input ground excitation are combined in the time domain.

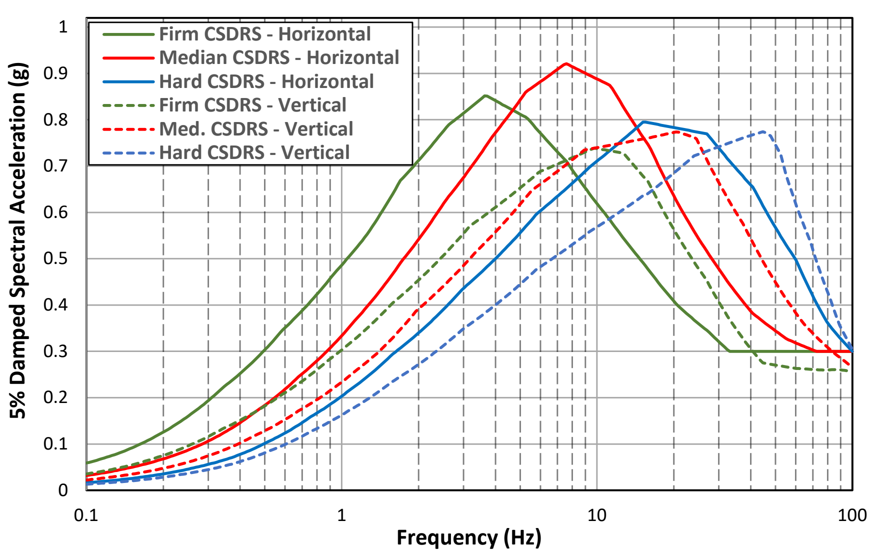

Figure 3. 5% damped Certified Seismic Design Response Spectra (CSDRS)

Table 2 lists the results of the eleven seismic SSI analyses for maximum in-plane shear and vertical axial forces in the below-grade outer shaft wall. Figures 4 and 5 present the results of four different seismic SSI analyses to illustrate their distribution. The in-plane shear forces are induced mainly by the horizontal ground excitation. The vertical stresses are a combination of the axial and bending stresses due to the horizontal response of the deeply embedded SMR structure induced by the vertical and the horizontal ground excitations, respectively.

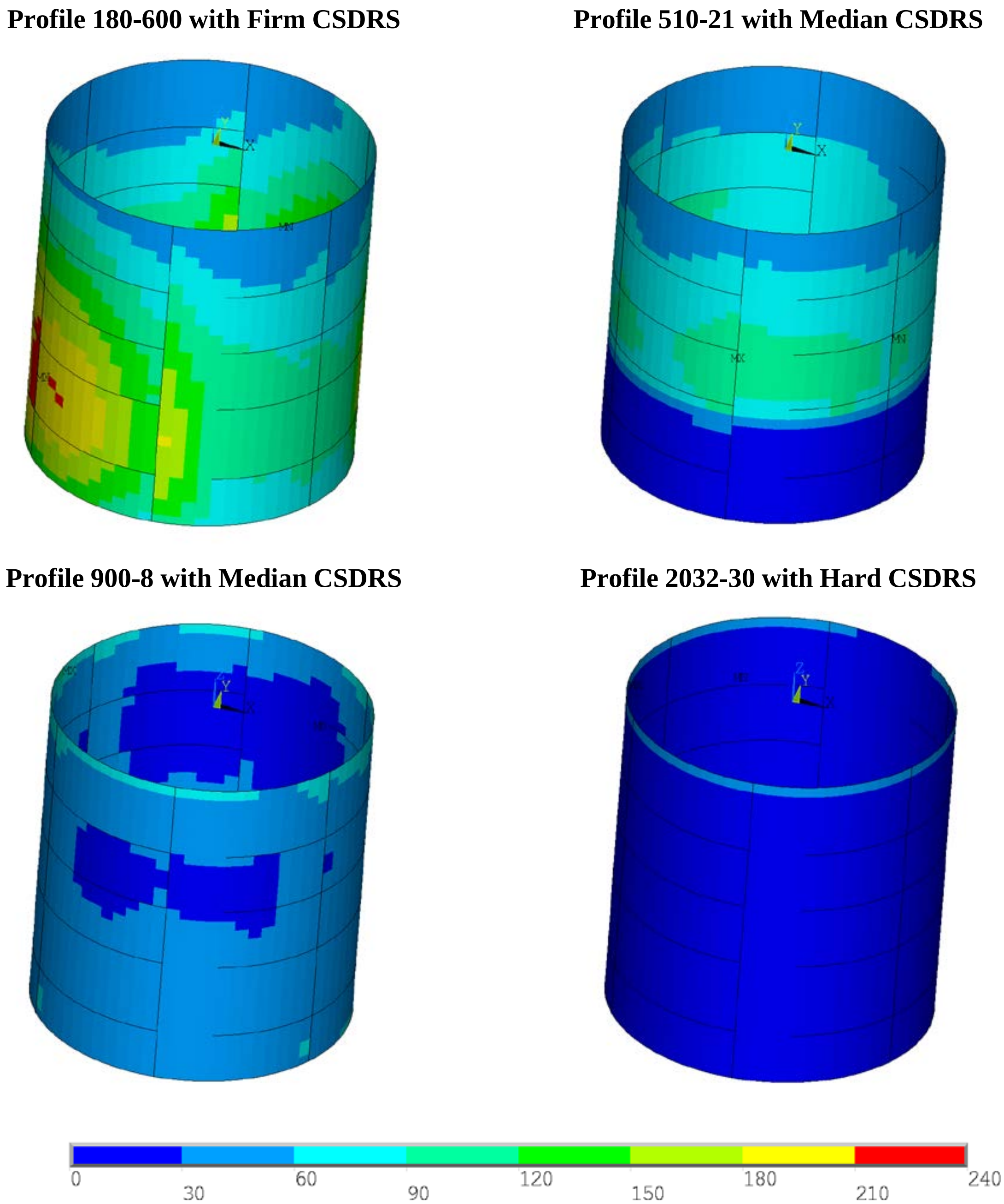

Figure 4. In-Plane Shear Forces in the Below-Grade Outer Shaft Wall (kip/ft)

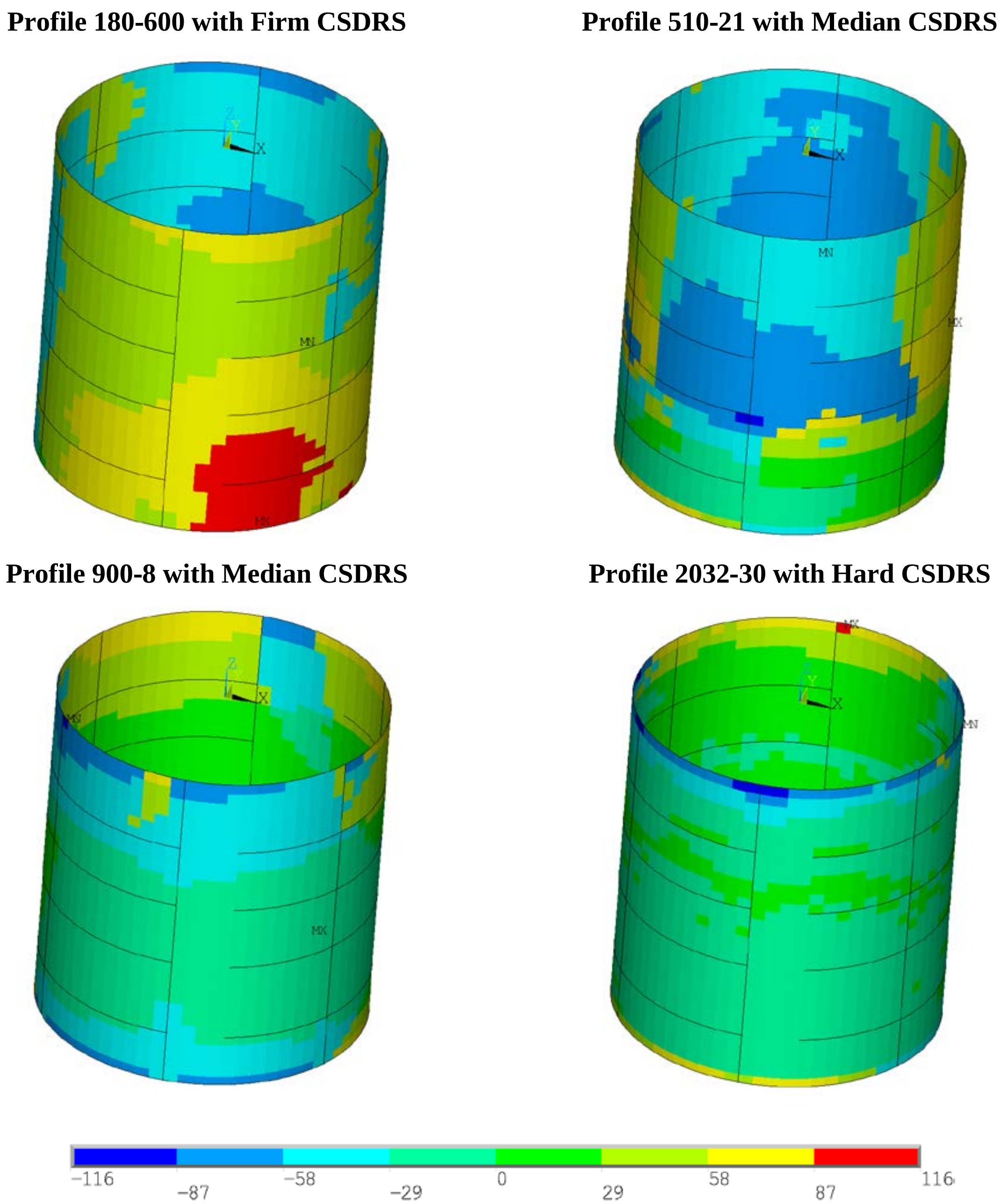

Figure 5. Vertical Stresses in the Below-Grade Outer Shaft Wall (kip/ft)

The maximum stress results listed in Table 2 and the stress distributions shown in Figures 4 and 5 indicate that the subgrade drives the response of the deeply embedded SMR structure. The largest stress responses are observed for the deep medium stiff soil site 180-600 that is subjected to a low-frequency ground motion represented by the Firm CSDRS. The analyses of rock profiles yield significantly lower stress responses due to horizontal ground motion excitation. The in-plane shear stresses obtained from analysis of Hard Rock High Frequency (HRHF) site 2032-30 being significantly lower than those observed for soil sites. The results of the analysis of the shallow soil profile 510-21 in Figure 4 illustrate how the transition from soil to rock results in a sudden reduction of the in-plane shear stresses in the outer shaft wall.

The comparison of maximum axial force results in Table 2 show that the vertical stress responses are a function of both the subgrade dynamic properties and the frequency content of the input ground motion. Larger vertical axial stress responses can be observed both for the deep medium stiffness soil sites and some of the rock sites driven either by the lower stiffness of the subgrade or the frequency content of the input motion and the lower dissipation of energy in the rock subgrades.

Figure 6 presents the horizontal and vertical 5% damped in-structure response spectra (ISRS) for the SMR seismic response at the top of the inner shaft containment wall located approximately 40 m above the SMR basemat elevation and 5 m above finished grade. The comparison of horizontal ISRS indicates that the SSI analyses with Median CSDRS yield the highest spectral accelerations in the frequency range between 2 Hz and 12 Hz, which is the most critical for the seismic design of most SMR safety-important equipment and components. The SMR seismic response displays the largest amplifications and peak spectral accelerations at a frequency of about 7 Hz for the soft (760-15) and firm (900-8) rock profiles, when subjected to Median CSDRS ground motion. The analysis of the firm rock profile 900-8 provides bounding ISRS for frequencies up to 14 Hz. As expected, the SMR experiences the largest high-frequency demands for the HRHF site 2032-30.   In the lower frequency range, the SMR horizontal response is dominated by the soil sites subjected to the Firm CSDRS, reflecting the compounded effect of the frequency content of the input motion amplified by the resonating soil column frequency.

The SMR response in the vertical direction does not exhibit much amplification in frequencies lower than 8 Hz, where the ISRS amplitudes reflect the frequency content of the input motions. Above 8 Hz, the Median CSDRS cases provide the largest response, followed by the Hard CSDRS cases at frequencies larger than about 12 Hz, where the individual peaks reflect the coincidence of the peak of the ISRS for the input motion with the resonant soil column frequency for different profiles as shown in the ISRS obtained from the SSI analysis of the deep soft rock profile 760-60 with Hard CSDRS. Similar to the horizontal direction, the HRHF site (2032-30) provides the largest in-structure responses in the vertical direction at high frequencies above 16 Hz, which is critical for the design of high-frequency sensitive equipment.

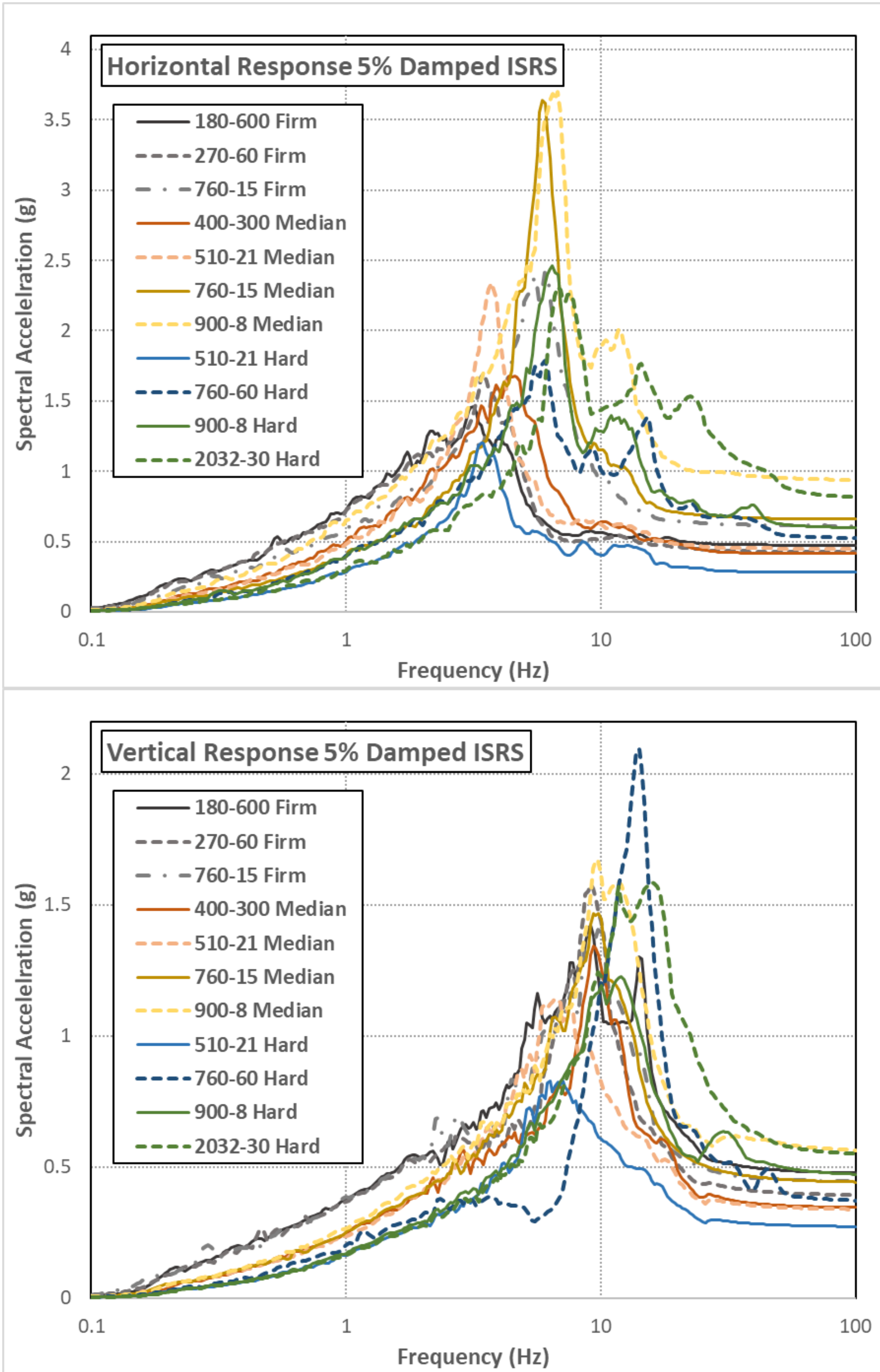

Figure 6. 5% Damped In-Structure Response Spectra (ISRS) for Response at Top of Inner Shaft

CONCLUSION

Results of the one-step approach static and seismic SSI analyses of a deeply embedded SMR structure are presented in this paper for a set of different types of geotechnical and seismological conditions present at the sites suitable for deployment of SMRs. Static SSI analyses are performed on a set of seven generic static subgrade profiles representing different types of soil and rock sites. The results of these static SSI analyses for the hoop membrane stresses in the below-grade exterior shaft wall are compared to evaluate how the geotechnical conditions at different types of sites affect the design of the deeply embedded SMR structure. The comparison of results of the generic static SSI analyses shows that the softer subgrade conditions, such as those present at deep medium stiff soil sites, result in the largest static earth pressure demands on the SMR structures.

A set of eleven generic seismic SSI analyses are implemented to evaluate the effects of different types of seismological and geotechnical site conditions on the seismic response and design of the deeply embedded SMR structure. A comparison is provided of the in-plane shear and vertical axial force responses of the below grade portion of the outer shaft wall. The comparisons show that the deep medium stiff soil sites result in the largest in-plane shear demands on the SMR structures. Larger seismic stress demands that can affect the design of the SMR structure are also observed for shallow sites at the interfaces of the softer surficial soil materials and the underlaying rock.

The ISRS results of generic seismic SSI analyses are also compared to evaluate the effects of different types of seismological and geotechnical site conditions on the seismic design of the SMR equipment, and components. The largest in-structure responses are observed at the soft and firm rock sites when subjected to Median CSDRS type of ground motions. The SMR in-structure responses at HRHF sites are the most critical for the design of high-frequency sensitive equipment. The SMR seismic response at lower frequencies is the largest for deep soil site conditions characterized by a Firm CSDRS type of ground motion.

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