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SSI PARAMETER SENSITIVITY CONSIDERATION FOR SMR SITE-SPECIFIC EVALUATION

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ABSTRACT

Soil-Structure Interaction (SSI) analysis is performed for a deeply embedded Small Modular Reactor (SMR) that is embedded to a depth of 34 meters in a site having 25 meters of medium stiff soil underlain by competent rock strata. Sensitivity evaluations are performed per guidance in Section 5.3 of NEDO 33914A (2021), to investigate the effects of the following SSI parameters on the seismic response and design of the deeply embedded SMR: (1) structural stiffness variation effects, (2) excavation support effects, (3) soil separation effects, and (4) groundwater elevation variation effects.

The sensitivity evaluations are based on results of sensitivity analyses on SSI models representing conditions that bound the variation of the evaluated SSI parameter. The results of the sensitivity evaluations highlight the importance of considering the effects of the variation of important SSI parameters, particularly in the case of the deeply embedded SMR. The results of these sensitivity evaluations show that variation of the important SSI parameters can be significant and as such, should be included in the SMR seismic design.

INTRODUCTION

The importance of the SSI parameters variations is evaluated for an approximately 60 m tall and 34 m wide SMR that is deeply embedded to a depth of approximately 34 meters in a site consisting of 24 m medium stiff soil underlain by competent rock strata. Per guidance of NEDO 33914-A (2021), the one-step approach structural design of the SMR is based on responses obtained from a finite element model (FEM) shown in Figure 1, that is refined enough to directly estimate forces and stresses for design of the main structural elements without the need for a second step of analysis. A ring of solid elements is placed around the SMR representing near-field subgrade materials. The surface-founded structures surrounding the deeply embedded SMR are also included in the SSI analysis model to account for the effects of Structure-Soil-Structure Interaction (SSSI).

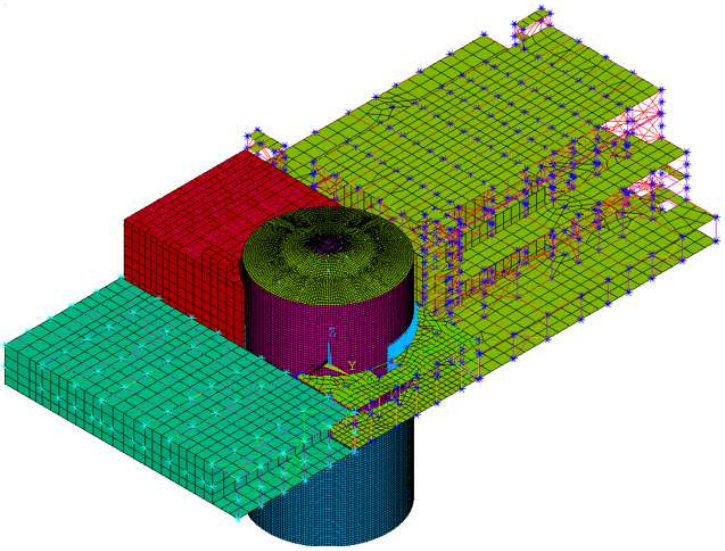


Figure 1. SMR SSI Analysis Model.

Per guidance in Section 5.3 of NEDO 33914-A (2021), the uncertainties related to variation of the site soil and rock properties are addressed by using seismic design demands obtained as envelope of results from SSI analysis of Best Estimate (BE), Lower Bound (LB), and Upper Bound (UB) subgrade dynamic profiles shown in Figure 2. BE effective stiffness properties are assigned to the concrete-made structural members in the FEM used for design basis SSI analysis. The near-field elements in the design basis SSI analysis models are assigned the same properties as the surrounding far-field subgrade.

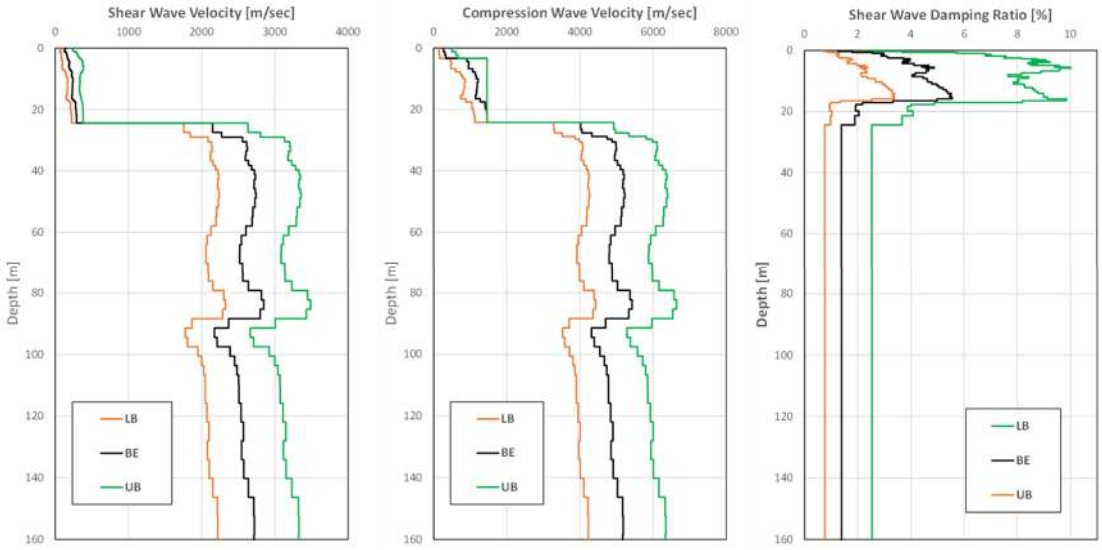


Figure 2. Subgrade Dynamic Properties.

The design of the SMR structure neglects the resistance provided by the excavation support and the lean concrete used to backfill the gaps between the SMR and the excavated soil and rock because their structural integrity is not guaranteed throughout the entire operational life of the plant. Furthermore, the design basis SSI analyses assume a perfect bond between the embedded SMR exterior wall and the subgrade emphasizing the ground motion propagation from the surrounding subgrade to the deeply embedded structure. Fully saturated conditions are considered for the soil below the nominal groundwater table elevation, which is located 3 m below the plant grade, that results in the maximum design ground water pressure loads on the SMR structure. To simulate saturated conditions, the soil Poisson's ratios are increased to reflect the compression wave velocity of water in the LB, BE and UB compression-wave velocity profiles used for the design basis SSI analyses.

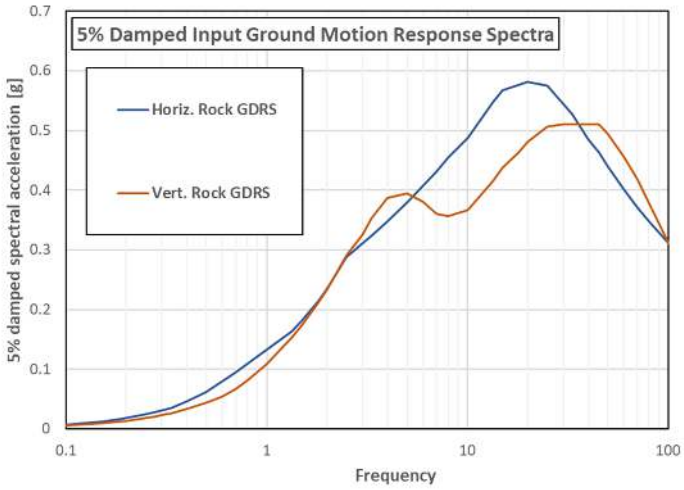


Figure 3. Input Ground Motion Response Spectra.

The control ground motion is input in the SSI model as a free-field motion defined at the bottom of the SMR by the Ground Design Response Spectra (GDRS) presented in Figure 3. SSI responses obtained from five sets of input motion acceleration time histories compatible to these GDRS are averaged to account for the uncertainties due to the phasing of the time history components.

EVALUATIONS OF SSI PARAMETER VARIATION EFFECTS

Results of sensitivity analysis performed on SSI models representing BE subgrade properties and conditions that bound the variation of important SSI parameters are compared with results of design basis SSI analyses to evaluate the importance of these effects on the SMR seismic response and design. These comparisons are performed for key response parameters, 5% damped In-Structure Response Spectra (ISRS) at key locations and main stress demands on key structural members. If the comparisons indicate that the effects can result in responses that are significantly (>10%) higher than the responses obtained from the design basis analyses, the results of the sensitivity analysis are incorporated in the seismic design basis.

The following sensitivity analyses are performed to investigate the effects on the seismic response and design of the deeply embedded SMR:

(1) ***Structural Stiffness Variation Effects***
In order to evaluate the effects of concrete cracking, a sensitivity analysis is performed on a model representing "lower bound (LB) stiffness" properties of SMR structures where all concrete-made members are assumed to be fully cracked in flexure and in-plane shear. A higher damping value is assigned to these structural members reflecting a higher level of dissipation of energy associated with the higher stresses resulting in cracking of the concrete.

(2) ***Excavation Support Effects***
A sensitivity analysis is performed on a SSI model having near-field elements assigned with stiffness properties simulating the effects of the excavation support and the lean concrete backfill to investigate their impact on the SMR seismic response and design.

(3) ***Soil Separation Effects***
To investigate the effects when for short instances of time, parts of the SMR below-grade exterior wall may separate from the surrounding subgrade, a sensitivity analysis is performed on a model simulating a complete separation between the SMR and the surrounding top layers of subgrade. The extent of soil separation is determined by comparing the maximum dynamic lateral earth pressures obtained from the design basis SSI analysis of the BE subgrade profile with lower bound estimates of the lateral static earth pressures. Based on this comparison, a depth of 15 m at which the seismic pressure exceeds the static lateral pressure is adopted as a separation depth for the evaluation of soil separation effects. To obtain more conservative stress demands on the SMR structure at and around the separation depth, the SSI model with concrete backfill is used.

(4) ***Groundwater Elevation***
A sensitivity SSI analysis of the BE soil profile reflecting "unsaturated soil" condition for all soil materials at the site are used to examine potential effects of groundwater level variability on seismic design. Unsaturated soil conditions are simulated by adjusting the Poisson's ratios of the soil materials resulting in compression-wave velocities lower than those used for the design basis analysis.

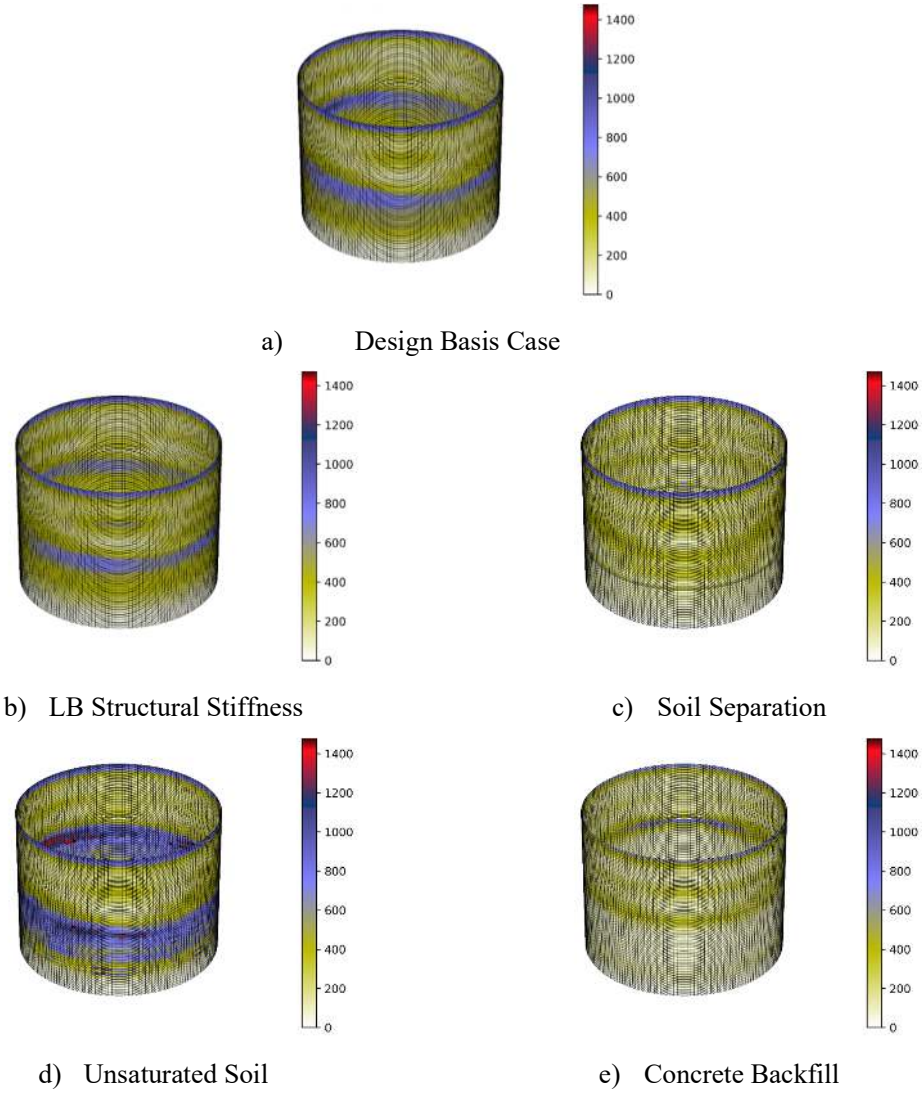
SENSITIVITY EVALUATION RESULTS

The effects of SSI parameters on the seismic stress demands on the SMR structure are illustrated herein by comparing main seismic structural member force demands on the below-grade portion of the exterior SMR wall as the structural member that is most affected by the SSI effects. The effects of SSI parameters on in-structure seismic demands are assessed by comparing 5% damped ISRS for responses

at two key exterior wall locations at the finished grade and roof elevations representative of the response throughout the SMR height.

SSI Parameter Effects on Force/Moment Seismic Load Demands

Figure 4 presents the estimated hoop forces in the exterior SMR wall, where the "Design Basis Case" refers to the BE profile case with the model properties used for the design basis calculations. The Design Basis Case forces are compared to those estimated for the four variations on the SSI parameters described earlier. Whereas the reduction of effective structural stiffness does not have any significant effect on the hoop forces, the separation of the soil at its interface with the exterior wall results in a significant reduction of seismic demands, and the same is observed for the concrete backfill condition where the additional lateral stiffness of the near-field elements acts to alleviate the stress on the exterior walls and to reduce the lateral dynamic pressures. In contrast, the unsaturated soil condition results in smaller values of Poisson's ratio for the surrounding soil, effectively reducing the lateral support for the exterior wall and increasing the seismic demands.



a) Design Basis Case

b) LB Structural Stiffness

c) Soil Separation

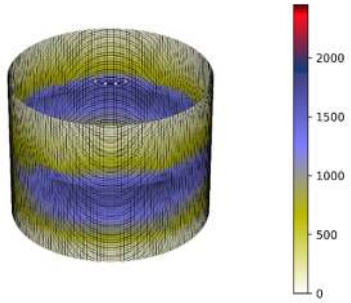
d) Unsaturated Soil

e) Concrete Backfill

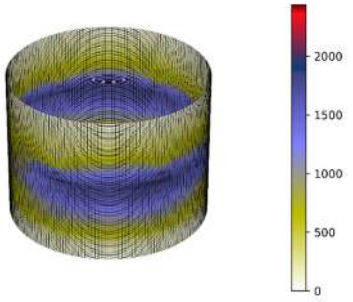
Figure 4. Effects on Exterior Wall Hoop Forces.

Figure 5 presents the vertical force demands in the exterior SMR wall for the Design Basis Case and the four SSI parameter conditions. Whereas the LB structural stiffness and the unsaturated soil

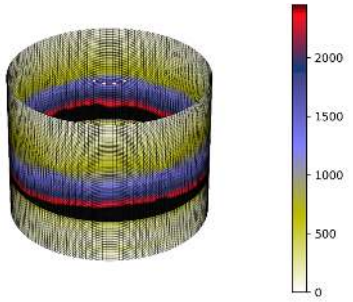
condition do not have any substantial effects on the vertical forces, the stiffer near-field concrete backfill conditions significantly reduce the vertical forces in the exterior SMR wall. On the other hand, the soil separation at the soil-to-wall vertical interface results in significant increase of the vertical forces below the separation depth of 15 m, down to the depth of 25 m corresponding to the depth of the surrounding rock stratum, where the surcharge load including that of the surrounding surface-founded structures is transmitted to the SMR structure.



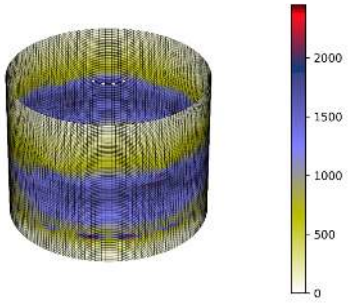
a) Design Basis Case



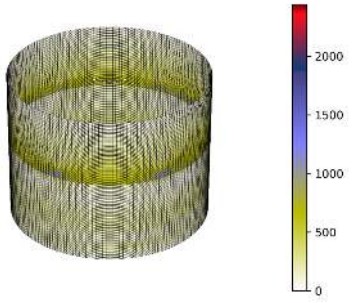
a) LB Structural Stiffness



b) Soil Separation



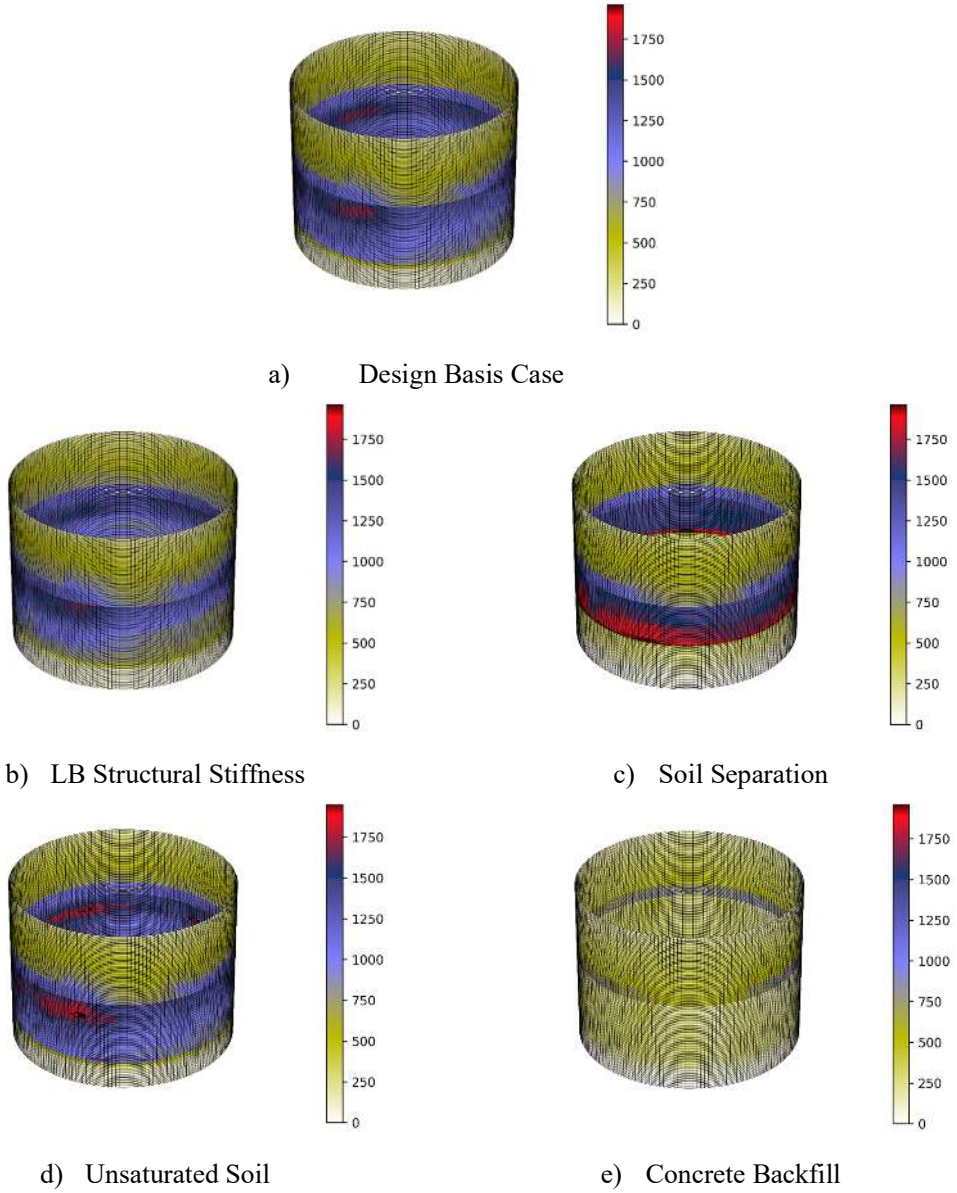
c) Unsaturated Soil



d) Concrete Backfill

Figure 5. Effects on Exterior Wall Vertical Forces.

Figure 6 presents the estimated in-plane shear forces in the exterior SMR wall for the Design Basis Case and the four SSI parameter conditions. Similar to the vertical force demands, the most noticeable differences are observed in the concrete backfill case where the seismic in-plane demands on the exterior SMR wall are significantly reduced, whereas the estimated in-plane shear forces increase substantially in the case where the exterior wall is separated from the surrounding soil.



a) Design Basis Case

b) LB Structural Stiffness

c) Soil Separation

d) Unsaturated Soil

e) Concrete Backfill

Figure 6. Effects on Exterior Wall In-Plane Shear.

SSI Parameter Effects on In-Structure Response

Figure 7 presents the 5% damped ISRS results for the SMR exterior wall response at finished grade in the two horizontal directions and in the vertical direction obtained from the Design Basis Case analysis of the BE profile and the four SSI sensitivity analysis cases, "Broadened ISRS" are also presented representing the envelope of the three design basis cases performed for the BE, LB and UB profiles. The peaks of these enveloping ISRS are broadened by a minimum of ±25% to address uncertainties related to the modelling of natural frequencies of the supporting structure and the SSI analysis methodology, and the sharp valleys between peaks are filled to account for the uncertainties in subgrade properties. Figure 8 presents the 5% damped ISRS for the SMR exterior wall response at the roof elevation.

The comparisons with the Design Basis Case show that the reduced structural stiffness and soil separation can result in a noticeable albeit small reduction in the fundamental horizontal response frequency of the SSI system, accompanied by a slight increase in amplitude. The unsaturated soil

condition does not significantly affect the response in the low frequency range. In contrast, the increased lateral support from the concrete backfill results in a substantial reduction of the horizontal response and an increase of the fundamental frequency of the SSI system response. In the vertical direction, the surrounding unsaturated soil results in a significant increase of the response at the high-frequency range (> 10 Hz), reflecting the reduced Poisson's ratios of the top soil layers and its effects on the amplification of the vertical motion.

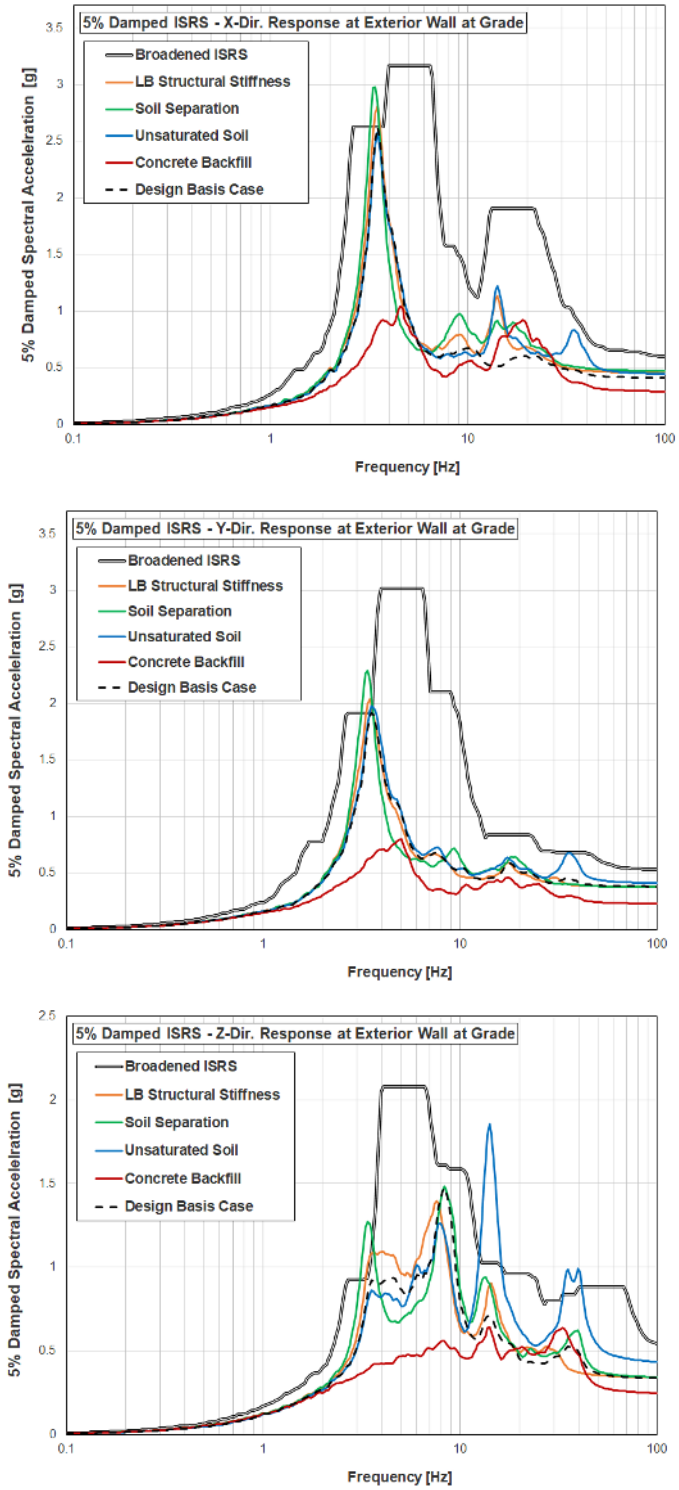


Figure 7. Effects on ISRS at Exterior Wall at Grade.

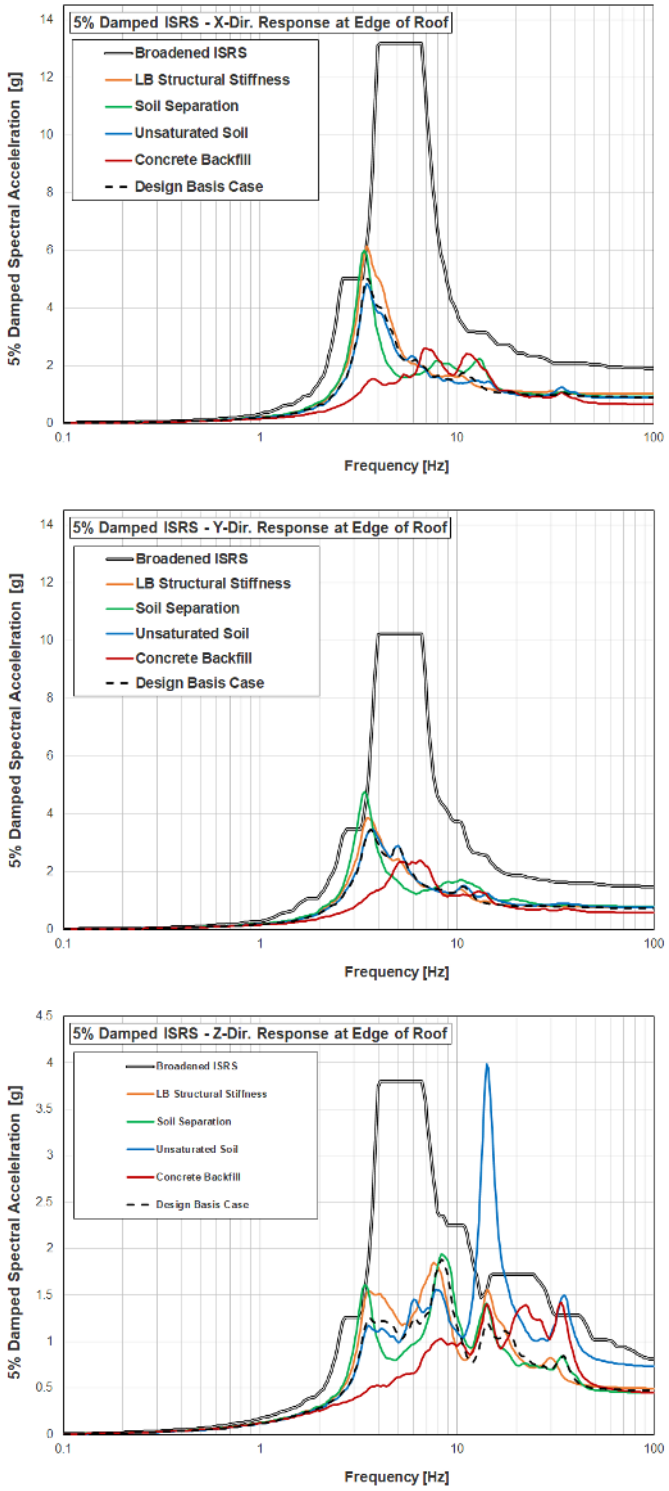


Figure 8. Effects on ISRS at Exterior Wall at Roof Elevation.

CONCLUSION

The effects of the variation of four SSI parameters on the SMR response are assessed by comparing the responses obtained from the design basis analysis with results of sensitivity analyses performed on models representing conditions that bound the variation of the evaluated SSI parameter. Some important observations from the evaluations are summarized below:

- The reduction of the structural stiffness does not have any significant effects on the seismic forces applied to the SMR exterior wall. Whereas the observed differences in the horizontal ISRS are minimal, noticeable increase in the vertical ISRS are expected due to the reduction in out-of-plane stiffness of the floor slabs.

- The separation of the soil from the exterior SMR wall can result in a significant decrease of the hoop forces due to the absence of seismic lateral earth pressure within the separated depth, and an increase of the vertical and in-plane shear forces below the separated depth due to the transmittal of surcharge loads from the surrounding surface mounted foundations to the exterior SMR wall at that depth. Whereas a noticeable increase can be observed in the vertical ISRS in the high-frequency range, the effect of soil separation on the horizontal ISRS is minimal.

- Unsaturated soil conditions can have a substantial effect on the seismic hoop force demands on the exterior SMR wall due to the reduced Poisson's ratios of the soil layers providing lateral support of the SMR. Another noticeable effect of the water variation effects is possible increase of the vertical ISRS in the high-frequency range, above 10 Hz.

- The stiffness from the excavation support and concrete backfill has the potential of significantly reducing the seismic demands on the below grade portion of the SMR structure, as well as the horizontal ISRS. On the other hand, the excavation support and the concrete backfill may result in increases in vertical ISRS in the high-frequency range.

The results of the sensitivity evaluations highlight the importance of considering the effects of the variation of important SSI parameters, on the seismic response and design of the deeply embedded SMR. The results of these sensitivity evaluations show that variation of some of these SSI parameters can be significant and as such, should be included in the SMR seismic design basis.

REFERENCES

GE Hitachi (2021) "BWRX 300 Advanced Civil Construction and Design Approach," NEDO-33914-A, (*https://www.nrc.gov/docs/ML2102/ML21020A137.pdf*), GE Hitachi Licensing Topical Report.