SEISMIC SOIL-STRUCTURE INTERACTION (SSI) EFFECTS FOR DEEPLY EMBEDDED NUCLEAR ISLANDS SURROUNDED BY SOFT BACKFILLS

D. M. Ghiocel, *Ghiocel Predictive Technologies, Inc., New York, USA*

ABSTRACT

This short paper addresses a technical subject topic of a special interest for seismic analysis of the deeply embedded nuclear islands surrounded by limited-size backfill soils that are significantly softer than the in-situ soil deposit. On this technical subject there is a lack of information in the published literature. To capture the backfill dynamic effects, the backfill soil must be included in the SSI FE model as a near-field soil. It should be noted that backfill dynamic effects impacts severely on the seismic SSI responses, especially on ISRS, both in the low and high frequency ranges depending on the backfill soil properties and sizes, and the seismic input frequency content. Motion incoherency and nonlinear backfill soil behaviour may also affect the backfill dynamic behaviour.

1. INTRODUCTION

If the limited-size surrounding backfill soil is much softer comparing with in-situ soil, the scattered wave energy is largely trapped in the backfill. The interface between the backfill and the much stiffer in-situ soil acts as a real reflective boundary in the physical space. For certain frequency intervals, the backfill motion can be highly amplified in comparison with the free-field soil motion. The computed in-structure response spectra (ISRS) could be significantly affected. The ISRS spectral peaks could be 50-100% larger, or even larger, due to the backfill soil dynamic behaviour.

Seismic motion incoherency and nonlinear backfill soil behaviour are additional influential factors that affect the backfill dynamic behaviour.

2. EXCAVATED SOIL MODELING ISSUES

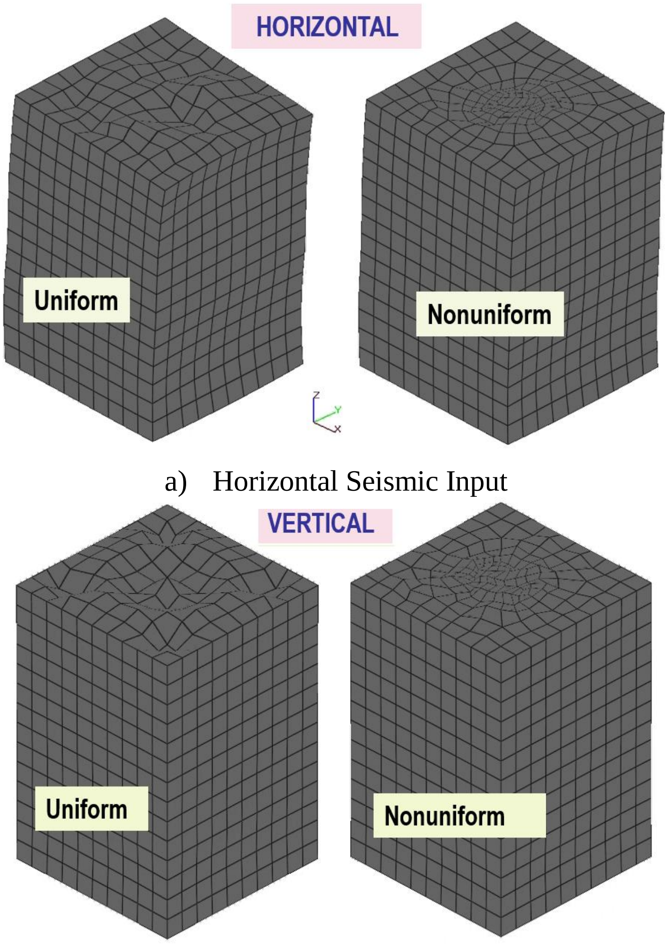
If the backfill soil is different than the in-situ soil, then, the surrounding backfill soil should be included in the SASSI FE model as a near-field soil. This increases the size of the entire SASSI FE model, that includes the structure FE model, the excavated soil FE model and the excavated soil FE model.

If the surrounding backfill soil is much softer than the in-situ soil layering, the required FE mesh should be much more refined for the backfill soil than for the in-situ soil layering. The refined mesh of the soft backfill soil is required for transmitting accurately the high-frequency wave components through the soft backfill material. However, if the refined soft backfill FE mesh is also used for the in-situ soil layering, then, the number of the interaction nodes explodes, and the computational SSI analysis effort increases largely by at least a magnitude order, if not much more.

For the soft backfill soil models, using a coarser regular FE mesh for the excavated soil model is highly beneficial not only for speeding up the SSI analysis by reducing the number of interaction nodes, but also for improving the accuracy of the SSI analysis. It should be noted that in a recent published BNL report authored by the USNRC BNL expert consultants [1], in the conclusion section it is stated that an important SSI modelling aspect to be addressed is "the need for regular excavated soil mesh for any reasonable FE structural model". The BNL report refers to typical situations when the bottom FE mesh of the structural model has an irregular mesh, due to the constraints from the complex geometries of the reactor buildings. Using the bottom irregular structure FE mesh to build the excavated soil FE mesh is not the most accurate SSI modelling practice.

To be able to define the excavated soil FE mesh as a regular mesh, transition mesh zones may be required to connect the structure FE mesh with the excavated soil FE mesh. This adds a new SSI modelling complexity for highly irregular foundation meshes, but the benefits obtained for the SSI analysis computational speed and its accuracy are highly rewarding.

Figure 1 shows the SSI motion of the excavation "pool" for a generic, deeply embedded SMR structure using a regular mesh ("uniform") versus an irregular mesh ("nonuniform") of the excavated soil. The plots show the excavated soil acceleration values at a given instant time in horizontal and vertical directions. The seismic input was a high-frequency content motion. It should be noted from Figure 1 that the excavation FE mesh quality impacts visibly on the wave scattering effects inside the excavation "pool". This is illustrated by the fact that the surface motions of the excavated soil are quite different for the two meshes. The differences are larger for the vertical input motion.



a) Horizontal Seismic Input

b) Vertical Seismic Input

Figure 1 Excavated Soil Acceleration Profiles for Horizontal and Vertical Directions

The SSI modelling complexity increases further for the FE models with surrounding soft backfill soil. To create an efficient and accurate SSI model with the soft backfill included, extended transition mesh zones might be needed to connect the soft backfill refined mesh with the excavated soil coarser mesh, as shown in Figures 2 and 3. By including these FE transition mesh zones between the backfill soil mesh and the excavated soil mesh (and in-situ soil layering) it is possible to create a regular mesh for the excavated soil. This improves the SSI analysis accuracy, and it is fully consistent with the SASSI theory as was pointed out by the USNRC consultants [1].

A typical detail of a 3D FE transition mesh zone for an embedded SSI model including in the near-field the surrounding soft backfill soil is shown in Figure 3.

It should be noted that the FE transition mesh zone should be a part of the in the in-situ soil material, not backfill.

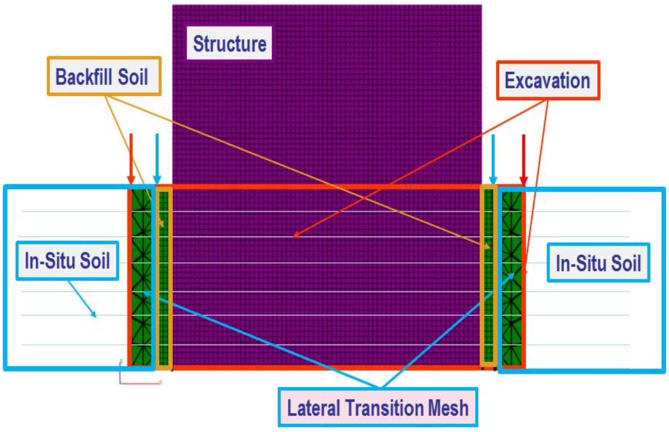


Figure 2 Embedded SASSI FE Model with Backfill Soil Mesh Included

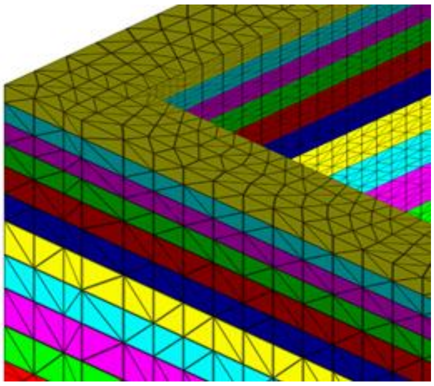


Figure 3 Lateral FE Transition Zone Detail

To validate that the FE transition mesh zones do not impact on the accuracy of the SSI analysis, comparative SSI analyses should be performed for the FE model with *no backfill* and *with backfill having a soil material identical with the in-situ soil*. The FE transition mesh zones, if done appropriately, should have no impact on the accuracy of SSI analysis. A typical validation comparison is shown in Figure 4. The transition mesh is similar with that in Figure 3.

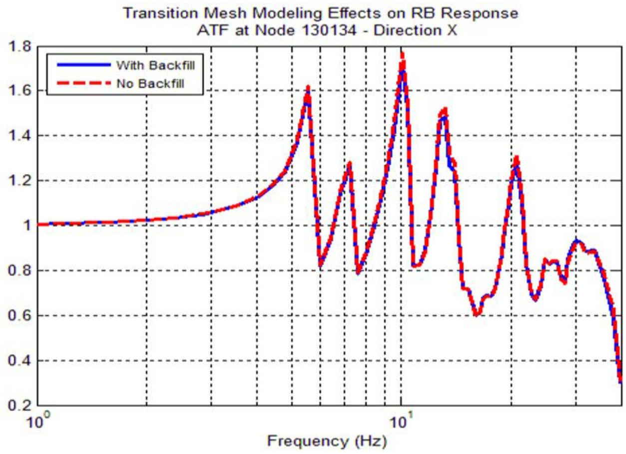


Figure 4 Computed ATF for the SSI Model Transition Mesh Validation; No Backfill vs. With Backfill

Figure 4 compares the acceleration transfer function (ATF) amplitude computed for a deeply embedded RB model with and without the backfill mesh included. The backfill soil and the in-situ soil properties were assumed to be identical. The computed ATF curves are overlapped, as expected for validation.

3. SOFT BACKFILL SOIL DYNAMIC EFFECTS

In this section we present few comparative results based on a seismic SSI sensitivity study done for a generic deeply RB complex considering different backfill soil properties and sizes. The ACS SASSI software [2] was used for the study investigations. The embedded RB structure FE model is shown in Figure 5. The oblique line indicates the ground surface position. The RB embedment is about 27 m. The basement of the RB model was further refined to match the refined mesh required for the soft backfill material.

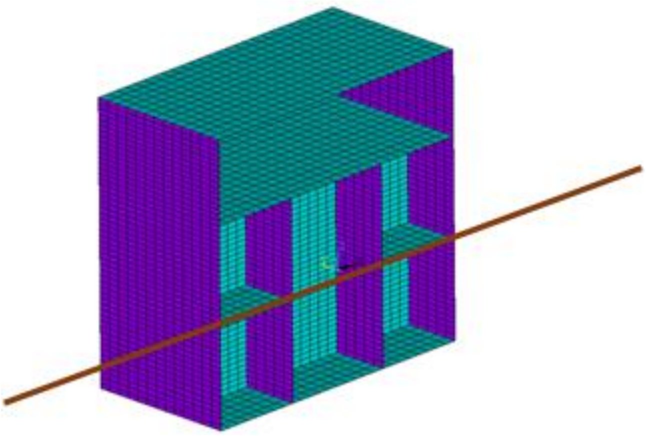


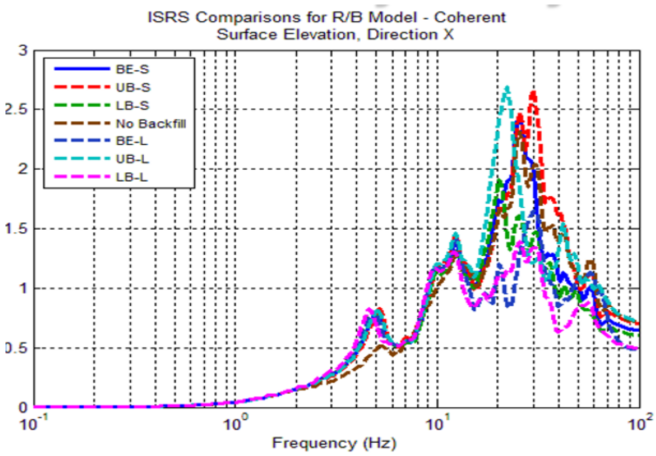
Figure 5 Deeply Embedded RB Complex Model

The in-situ soil deposit was assumed to be an uniform geological rock formation with a best-estimate Vs = 2,500 m/s. The backfill soil Vs was assumed to be only 200 m/s for the lower bound (LB), 300 m/s for the best-estimate (BE) and 400 m/s for the upper bound (UB). The backfill width was assumed: a) Small width of 2.5m (denoted by letter S in plot legends) and b) Large width of 5m (denoted by letter L in plot legends).

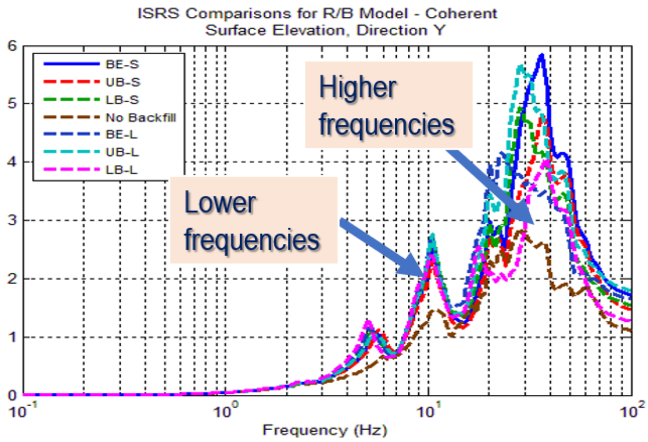
The seismic input ground motion was defined by a typical Eastern US HRHF motion which is described by a GRS with a maximum amplitude in the 20-40 Hz frequency range as used in the 2007 EPRI studies for validating the high-frequency seismic SSI analysis approaches [3].

For the SSI sensitivity studies, six cases were considered for the backfill soil modelling, assuming three different material properties (LB, BE, UB) and two width sizes (S, L). The six cases are LB-S, BE-S, UB-S, LB-L, BE-L and UB-L. For comparison purposes a separate case for the SSI model with no backfill soil included was also considered. Thus, a total of seven SSI cases were compared.

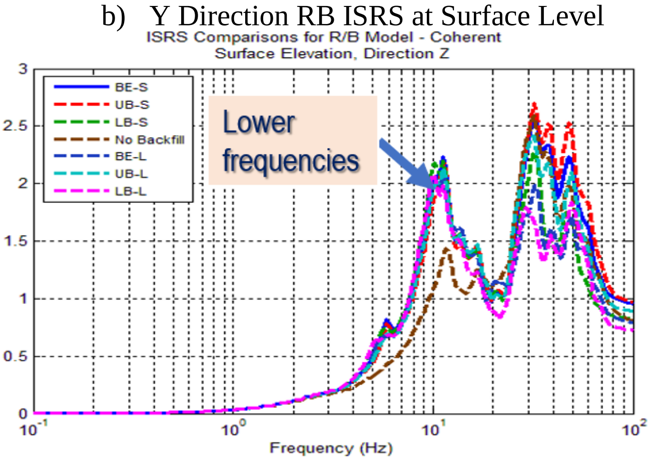
Figure 6 shows comparatively the computed in-structure response (ISRS) for the seven cases at a location selected within the RB complex at the ground surface elevation, in X, Y and Z directions.



a) X Direction RB ISRS at Surface Level



b) Y Direction RB ISRS at Surface Level



c) Z Direction RB ISRS at Surface Level

Figure 6 Comparative RB Complex ISRS for the Seven SSI Backfill Modelling Cases

The sensitivity study results, as shown in Figure 6, indicated that the backfill soil dynamic effects could largely affect the computed ISRS in both low- and high-frequency ranges. ISRS amplitude increases of up to 100% are shown in Figure 6. Similar results were obtained for many other locations within RB complex.

Due to the surrounding soft backfill soil there is an amplification of the ISRS peaks in the low-frequency (LF) range due to the significant additional mass attached to the structure by the soft backfill soil material that has a low stiffness but a quite large mass. Also, there are large amplifications of the ISRS peaks in the high-frequency (HF) range due to the localized soft backfill vibration modes excited by the high-frequency seismic ground motion. These effects are visually explained in Figure 7.

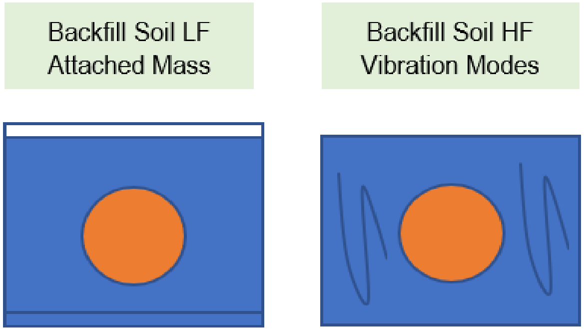
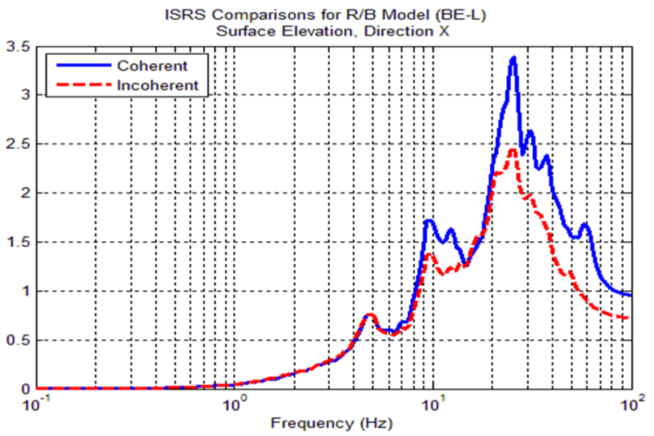


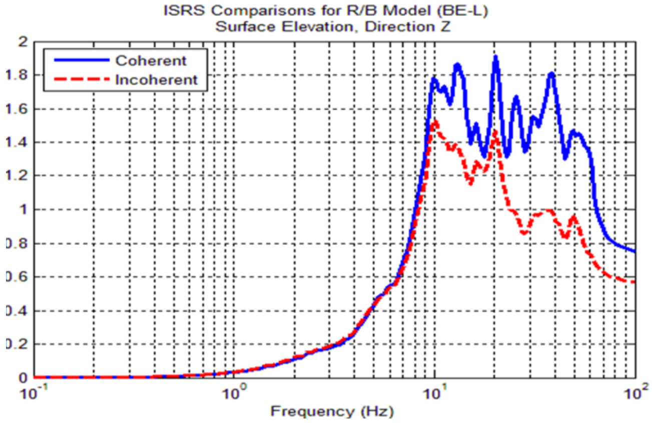
Figure 7 Soft Backfill Soil Material (Blue) Dynamic Effects for Cylindrical RB Structure (Brown)

During the SSI sensitivity study on the soft backfill dynamic behaviour impact on the computed ISRS, there were also investigated the effects of the motion incoherency and the backfill soil nonlinear behaviour on the RB complex ISRS. Herein, we select only a few ISRS locations as representative examples.

Figure 8 shows the effects of the motion incoherency on ISRS selected at a different RB location than in Figure 6, in the horizontal and vertical directions.



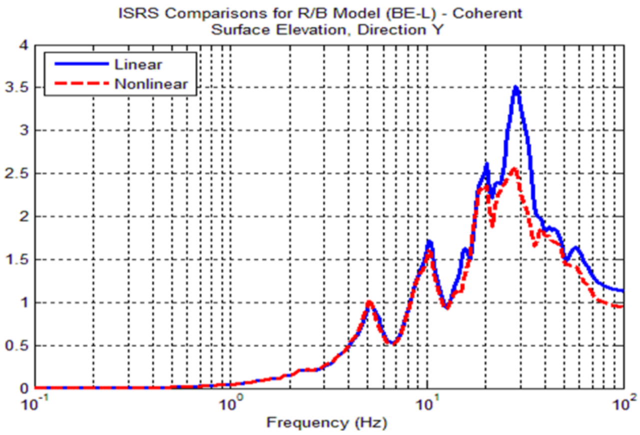
a) Horizontal ISRS at Surface Level



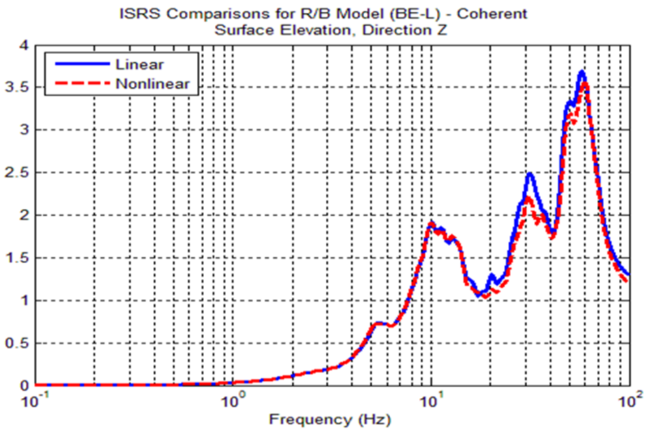
b) Vertical Direction ISRS at Surface Level

Figure 8 Comparative Incoherent-Coherent ISRS for the SSI Model BE-L Case

Figure 9 shows the effects of the soft backfill soil behaviour on ISRS in the horizontal and vertical directions. To include the nonlinear hysteretic backfill material behaviour, iterative SSI restart analyses were performed. The ACS SASSI software [2] allows these fast SSI iterations to be done automatically based on the computed octahedral strains in the soil elements.



a) Horizontal Direction ISRS at Surface Level



b) Vertical Direction ISRS at Surface Level

Figure 9 Comparative Linear-Nonlinear ISRS for the SSI Model BE-L Case with Coherent Inputs

Figures 8 and 9 indicate that the effects of both the motion incoherency and the soft backfill soil nonlinear hysteretic behaviour on the RB complex ISRS are quite significant. Both effects reduce the high-frequency ISRS peaks in the horizontal direction, but only incoherency reduces the ISRS peaks in the vertical direction. As shown in Figure 9b, the backfill nonlinear behaviour has minimal effects on the vertical ISRS.

4. CONCLUSIONS

The paper investigates the effects of the soft backfill soil dynamic behaviour for a generic deeply embedded RB building founded on a rock site subjected to a high-frequency seismic ground motion. These backfill soil effects are significant on the ISRS for both the low- and high-frequency ranges.

The backfill soil dynamic effects on ISRS depend on the backfill properties and sizes as shown herein.

The backfill soil effects on ISRS are also affected by other influential factors, as motion incoherency and nonlinear backfill material nonlinear behaviour as illustrated by this paper results.

The in-situ soil stiffness relative to the backfill soil stiffness is a potential influential factor that will need to be investigated in future.

5. REFERENCES

1. Nie, J., Braverman, J., and Costantino, M. (2013). “Seismic Soil-Structure Interaction Analyses of a Deeply Embedded Model Reactor – SASSI Analyses”, *U.S. Department of Energy, Brookhaven National Laboratory, BNL 102434-2013, New York*

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3. Short, S.A., G.S. Hardy, K.L. Merz, and J.J. Johnson (2007). “Validation of CLASSI and SASSI to Treat Seismic Wave Incoherence in SSI Analysis of Nuclear Power Plant Structures”, *Electric Power Research Institute, Palo Alto, CA and US Department of Energy, Germantown, MD, Report No. TR-1015111, November*