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CONSIDERATION OF NON-UNIFORM EMBEDMENT ON THE RESPONSE OF NUCLEAR PLANT STRUCTURES

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ABSTRACT

The effects of foundation embedment on the seismic response of structures have long been recognized in the analysis and design of nuclear power plant (NPP) structures. Some design standards allow simple methods to address the embedment effects. However, these methods are only suitable to consider the effects of soil embedment on uniformly embedded structures. There is no prescribed procedure to consider the embedment effects on non-uniformly embedded structures, which are typically found in many NPPs. Systematic sensitivity studies could prove useful in such cases to identify an appropriate approach which reasonably considers the embedment effects. This paper examines the seismic soil-structure interaction (SSI) response of two non-uniformly embedded structures as case studies. The first case includes three rock-founded Reactor Buildings (RBs) which are constructed side by side and are embedded in soil. Two smaller Diesel Generator Buildings (DGBs) are founded on the sides of the RB block at grade level. The objective of this study is to determine whether an SSI model that includes one RB only, instead of a complex model including all buildings, could reasonably provide the response in all three RBs, despite the differences in embedment configurations and potential SSSI effects in each of the RBs. It is shown that the SSI model that only includes embedment on two sides of a single RB, while neglecting the DGBs, can reasonably represent all three RBs, without meaningfully sacrificing accuracy. The second study includes an intake structure (IS) founded on bedrock and embedded in soil on three sides, while facing water on the forth side. It is shown that the treatment of the intake structure as partially embedded on 3-sides with the top 20 ft. of embedment separated from the building produces reasonable results. An important conclusion drawn from these case studies is that non-uniform embedment can be reasonably considered in many cases when using equivalent linear analysis tools, and that conducting systematic sensitivity studies can result in efficient and cost-effective solutions for idealizing such embedment conditions.

INTROCUCTION

Foundation embedment generally results in some increase of the natural frequency of the structural behaviour, and a reduction of the structural response, compared to the same structure founded on soil surface. Decrease in structural response is due to increased radiation damping and lower net input ground motion. Embedment effects are often addressed for nuclear facilities as part of SSI analysis via sub-structuring techniques such as is adopted in the SASSI family of computer programs [Lysmer et al. (1981)]. These techniques are well suited to consideration of uniform embedment, where a structure on a flat site is partially embedded to the same elevation around its entire perimeter. However, the physical configuration of nuclear facility structures and foundations rarely reflects the idealized embedment conditions assumed in typical SSI analysis guidance. For example, limited tensile and/or friction capacity of the soil/structure interface can lead to partial separation of the embedded foundation from the surrounding soil; an embedded foundation that partially separates from the soil behaves differently than the more fully embedded case or the surface-founded case. Another example is the case of an embedded structure build immediately adjacent to another embedded structure, such that there is no embedment soil between the structures, resulting in each structure having effective embedment on only a portion of its perimeter. A third example involves topographic features causing different parts of a structure's perimeter to have drastically different embedment depths, such as a slanting site or a shoreline structure. In such "non-uniform" embedment cases, and where equivalent-linear properties are required to comply with sub-structuring techniques such as in SASSI, the SSI analyst often makes an engineering judgment to select an embedment idealization that can be justified as sufficiently conservative. However, where conservatism is either not desirable or is difficult to discern via judgment, the SSI analyst may seek an understanding of the specific effects of embedment non-uniformity to reasonably idealize embedment conditions.

Some design standards such as ASCE 4-16 (2017) allow simple methods to address the partial soil separation of embedded foundations (the first example identified above) by removing connectivity between the structure and surrounding soil over a certain depth, or by reducing soil stiffness adjacent to the walls. While these simplified code-based methods may reasonably consider the effects of soil embedment on uniformly embedded structures, there is no prescribed procedure to consider the embedment effects on non-uniformly embedded structures (such as the second and third examples identified above), which are typically found in many NPPs. Systematic sensitivity studies are one typical approach that prove useful to ascertain the significance to response of the embedment non-uniformity.

This paper examines the seismic soil-structure interaction (SSI) response of two non-uniformly embedded structures as case studies. Both case studies involve multiple simultaneous non-uniformity of embedment conditions. These structures were analysed via Finite Element (FE) models considering SSI effects in SC-SASSI (2018) as part of seismic probabilistic risk assessment (SPRA) of a major NPP, wherein realistic (versus grossly conservative) structural response estimates were desirable. These studies correspond to the RB+DGB and IS SSI models as representations of NPP structures. The control point for both studies is at the top of the bedrock at EL 515'. The input motion for both studies is also the same and is based on the time histories matched to the 1E-5 AFE Uniform Hazard Spectra (UHRS) as shown in Figure 1.

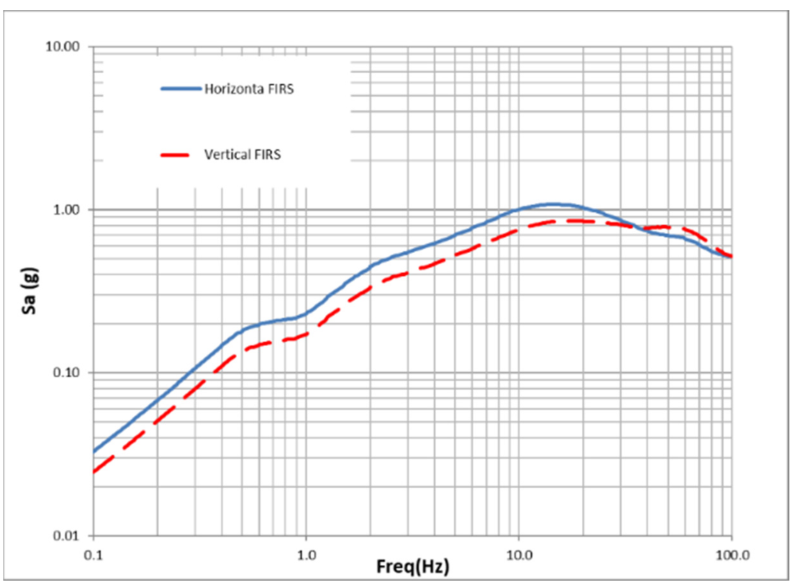
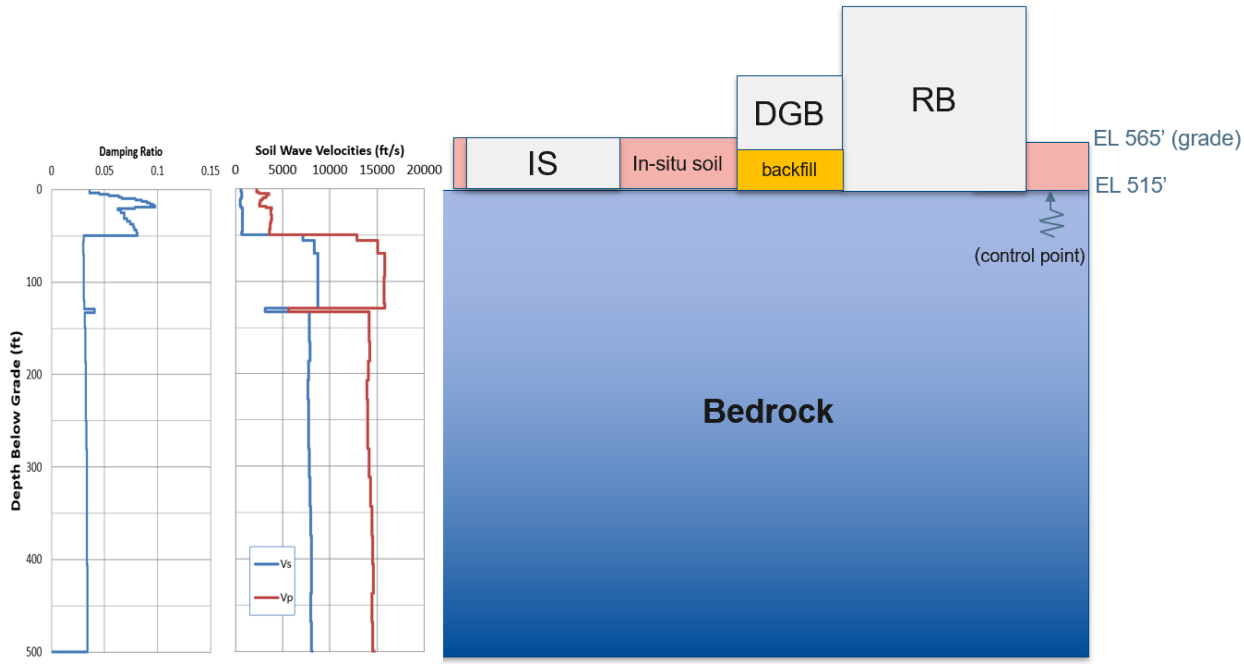


Figure 1: 1E-5 AEF outcropped FIRS on top of the bedrock

The soil properties are consistent with the 1E-5 Annual Exceedance Frequency (AEF) ground motion as shown in Figure *2*.



Soil and backfill density=120 lb/ft^3

Figure 2: Strain compatible soil profile and the location of the control point for the case studies

CASE STUDY 1:

This case study investigates the non-uniform embedment condition resulting from the construction of three (3) adjacent Reactor Buildings, bookended by two (2) Diesel Generator Buildings. The objective is to identify a reasonably sized SSI model that can be used to reasonably represent the response in all RBs, in lieu of an extensive SSI model that includes all buildings within the RB-DGB complex, despite the differences in the embedment conditions and potential SSSI effects from adjacent structures. The advantage of using one SSI model representing all three RBs is significant saving in the computational resources, project time, and cost, by reducing the number and size of SSI models needed to generate the response in the three RBs.

Description of the structures

The RBs are founded on rock at about 50 ft. below the ground surface (EL 515') and are embedded in the in-situ soil. There is a soil berm (with a height of approximately 30 ft) on the south side, and a Turbine Building (TB) on the north side of the RB complex. Due to the overburden pressure caused by the TB and the soil berm, no soil separation is expected between the RB and the surrounding soil at the seismic hazard level of interest. Each RB has a footprint of roughly 200ft x 200ft and weighs about 215,000 kips. The two DGBs on the west and east sides of the RB complex have footprints of roughly 70ft x 106 ft and 90 x 106 ft, and weights of about 17,000 kips and 22,000 kips, respectively. The DGBs are founded on backfill material with their top of the foundation situated at grade (EL 565'). A general view of the structure arrangement is shown in Figure *3*. Because of the structural configuration described above, while the RB-1 and RB-3 are adjacent to engineered fill below their respective adjacent DGBs, RB-2 is only embedded on the north and south sides.

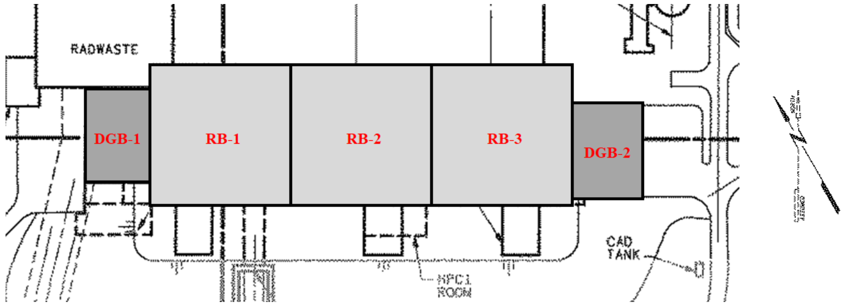


Figure 3: RB and DGB Configuration Layout

The base model used to generate the study cases is the RB-1 combined with the adjacent DGB Finite FE model as shown in Figure 4. Linear elastic material properties are used to represent the structural material. The FE model is developed using shell, solid, beam, spring, and matrix elements to represent the structural components.

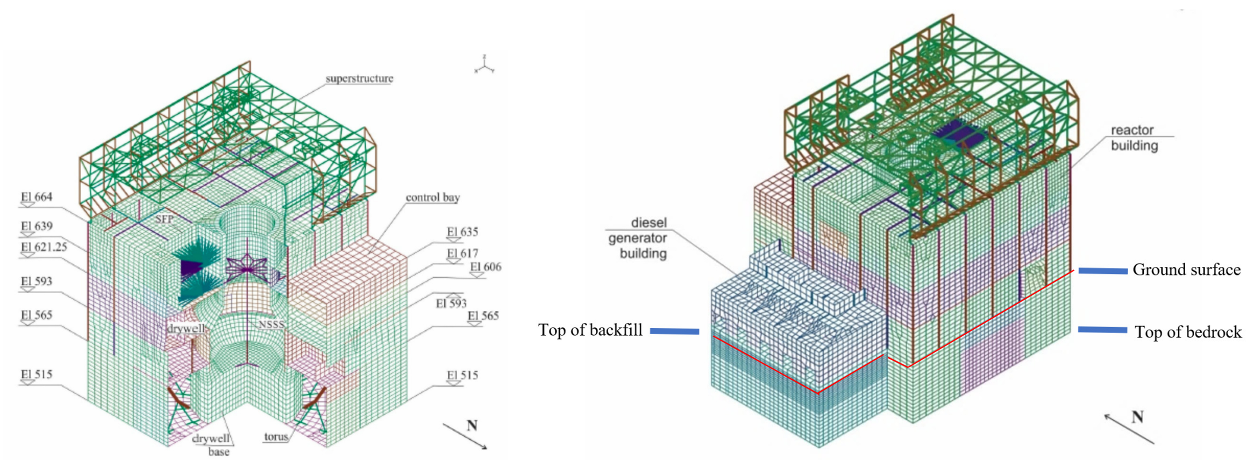


Figure 4: Case Study 1. left) Northwest view of the RB model, right) Northeast view of the RB+DGB model

Case study 1 evaluation method

Four SSI models have been generated and evaluated to capture potential SSSI effects and various embedment conditions:

1. RB Surface Founded SSI Model: This is the surface founded SSI model without consideration of embedment or effects from the DGB. It is included in the study to investigate whether the embedment has any significant effects on the response of RB.

2. RB+DGB 3-Sided Embedment SSI Model: The 3-Sided Embedment with the inclusion of the DGB unit best represents the as-built embedment conditions for RB Units 1 and 3. Embedment on the opposite side of the DGB (west side of RB) has been omitted by separating the structure nodes from the soil nodes. The backfill below the DGB is modelled as part of the structural model with 3D solid elements connected to the RB foundation wall. Full embedment is maintained on the east, north and south sides of the RB model up to the surface grade (i.e. the earth berm is neglected.).

3. RB 2-Sided Embedment SSI Model: This model best represents the embedment condition for RB Unit 2 and omits the DGB structure and backfill. This model can also represent RB Units 1 and 3 if the effect of the DGB structure and backfill on the RB response is found to be insignificant. Embedment has been omitted on the east and west sides of the RB by separating the structure nodes from the excavated soil nodes, while maintaining full embedment on the north and south sides of the RB model up to the surface grade (i.e. the earth berm is neglected.).

4. BFN RB 2-Sided Embedment SSI Model "Released": This model is identical to Study Model 3 but is modified to contain interaction nodes for embedment connected to the structure in the lateral directions only with the tangential directions released, by using zero-length rigid springs. This model serves to study the effects of the omission of soil friction (traction).

SSI analyses are performed using the modified subtraction method where interaction nodes are defined at the soil-structure interface and at grade elevation, enhanced with an additional layer of interaction nodes roughly halfway through the embedment height. In addition, all interaction nodes under the DGB foundation are included to account for impedance effects of the engineered backfill.

Case study 1 results

Example ISRS response at 5% damping for all four models at selected locations across the height of the RB structures is shown in Figure 4. The following observations can be made:

Evaluation of ISRS at select locations show that SSI model 1, corresponding to the surface founded RB SSI model, produces conservative (high amplitude) ISRS response. The degree of conservatism is such that the use of the surface founded model is not recommended for generation of realistic ISRS.

Comparison of SSI models 2 and 3 (corresponding to 3-sided embedment including the DGB, and 2-sided embedment without the DGB respectively) indicates that the inclusion of the DGB in the SSI model generally does not have a significant effect on the response of the RB, as the results between these two cases do not show significant difference.

Comparing the response between SSI models 2, 3, and 4 generally show lowest response for model 2, the 3-sided embedment case with inclusion of the DGB, and highest response in model 4, the 2-sided embedment case without inclusion of soil friction. The 3-sided embedment model including the DGB, represented with SSI model 2 is not a fair representation of the embedment condition and structural layout for RB Unit 2, and could therefore produce artificially low response when used for SSI analysis on Unit 2. Also, SSI model 4, which omits the effects of soil friction, may be overly conservative, as in reality, at least partial soil friction will be present between the structure and soil interface, especially due to soil surcharge loads from the earth berm that has been neglected in the model and the TB.

Conversely, SSI model 3, which considers 2-sided embedment and includes effects of soil friction, shows response that generally envelopes the ISRS response due to embedment conditions and structural configuration of SSI model 2, while not producing overly conservative results as seen in model 4. Based on this comparison, it can be concluded that the embedment conditions and structural model from model 3 is the most suitable model that can reasonably produce the response for all RB units.

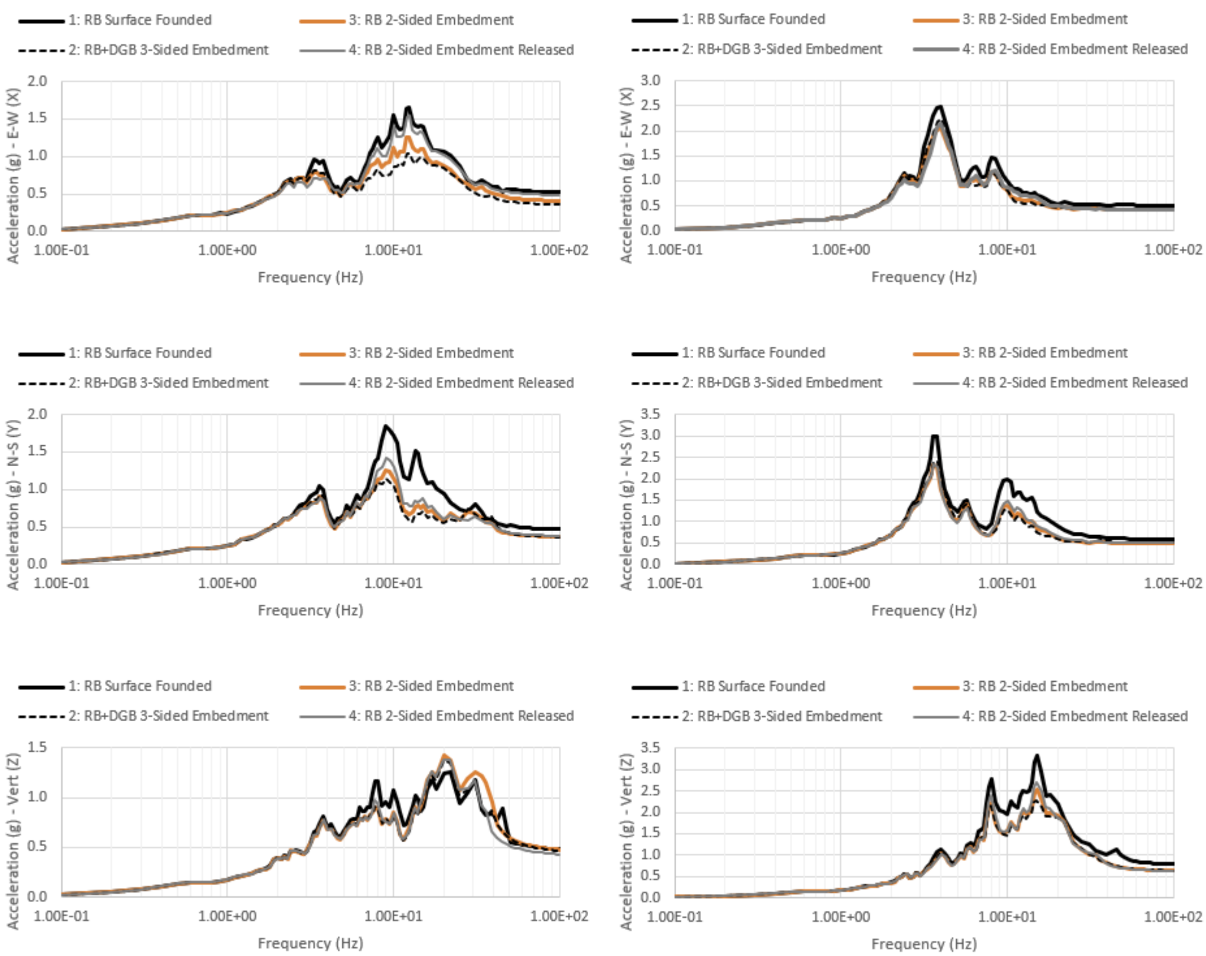


Figure 5: RB typical ISRS. left) EL 565’, right) EL 621’

CASE STUDY 2

This case study investigates the non-uniform embedment condition resulting from the unbalanced 3-sided embedment, which is typical to intake structures in many NPPs. The objective is to find the optimal SSI model with appropriate consideration of embedment that can be used to reasonably represent the response in an intake structure.

Description of the structure

The IS is an 81 ft. x 232 ft. structure founded on bedrock. It is backfilled with soil on three sides on the north, east and west, and faces water on the south side. Figure 6 shows an isometric view of the IS FE model, along with the FE model of the excavated soil.

Case study 2 evaluation method

In order to select the final approach for treatment of the embedment in the IS, four different embedment scenarios are investigated:

1. No embedment: the IS is considered surface founded to investigate whether the embedment has any significant effects on the response.

2. 4-sided embedment: even though the IS is physically embedded on three sides, the south side of the IS is also considered embedded in this case, to investigate whether full embedment has a significant effect on the IS response.

3. 3-sided full embedment: to simulate 3-sided embedment, the soil and structure are "released" on the South side of the SSI model by separating the structure nodes and the coincident soil excavation model nodes.

4. 3-sided partial embedment: in addition to removing embedment on the South side, embedment is also removed at the top 20 ft. of the embedded sides of the structure consistent with recommendation given in Section 5.1.9 (b) of ASCE 4-16 (2017) to mitigate artificial tension in the soil at the contact interface with the structure (especially on the north side opposite the water). This is accomplished by separating the excavated soil model nodes and the structure nodes at the upper 20 ft.

The detailed FE model is developed using shell and beam elements to represent the structural components. Linear elastic material properties are used to represent the structural materials. SSI analyses are performed using the direct method where interaction nodes are defined at all excavated soil nodes.

Case Study 2 Results

Example ISRS response at 5% damping for all four models at two selected nodes, namely nodes 2996 and 2023 are shown in Figure 7. These two nodes correspond to typical equipment locations near the west external wall, and a typical equipment location near the center of the building. A summary of the results and conclusions is provided below:

Horizontal response: The embedment reduces the response significantly at frequencies beyond 5Hz. The reduction is about 30%~70% depending on how the embedment is considered. Based on the results, due to the significant conservatism in the surface founded model, its use for generation of response is not realistic. The 3-sided and 4-sided fully embedded models both show relatively similar ISRS in x direction. However, the results of these two cases are lower than the 3-side partially embedded models where the embedment at the top 20 ft. of the model is removed. As expected, the ISRS amplitudes resulting from partially 3-side embedded IS models are lower than the surface founded case, but higher than the fully embedded cases where artificial soil tension and friction causes unconservative response reduction. The partially embedded case is considered more realistic since it properly considers the lack of soil tension between the soil and structure. Therefore, use of partially embedded model is considered appropriate for generation of response.

Vertical response: The surface founded ISRS amplitudes are generally higher. The 4-sided fully embedded case shows higher ISRS amplitudes than the 3-sided embedded cases at frequencies between 15Hz and 25Hz. This is expected because more energy is transferred from the soil to the structure through the side walls in the 4-side fully embedded case due to the additional embedment on the south side of the IS. However, since the actual embedment of the IS does not have 4-sided embedment, the amplification of the response centered around the soil column vertical frequency (18 Hz) is not expected to be as high as is shown by the 4-sided fully embedded model in reality. This observation is best demonstrated by the vertical response of node 2996, which is closer to the embedded wall than node 2023.

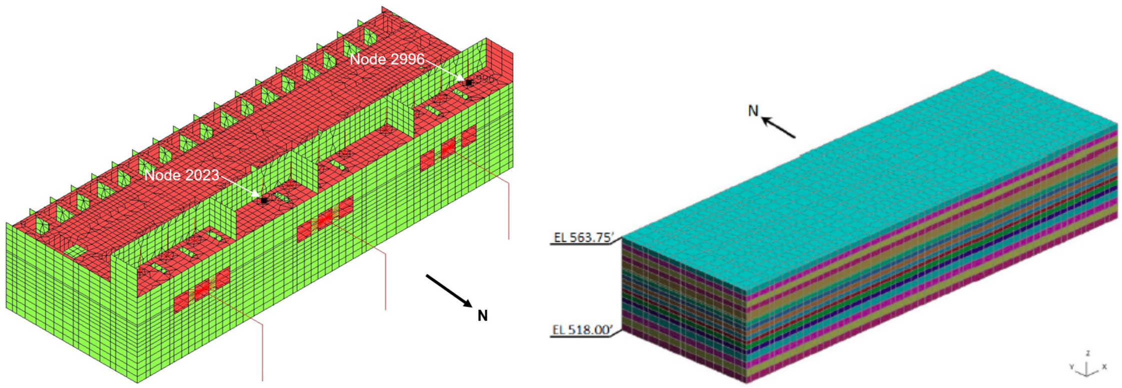


Figure 6: Case Study 2. left) Southwest view of the IS FE model, right) Southwest view of excavated soil

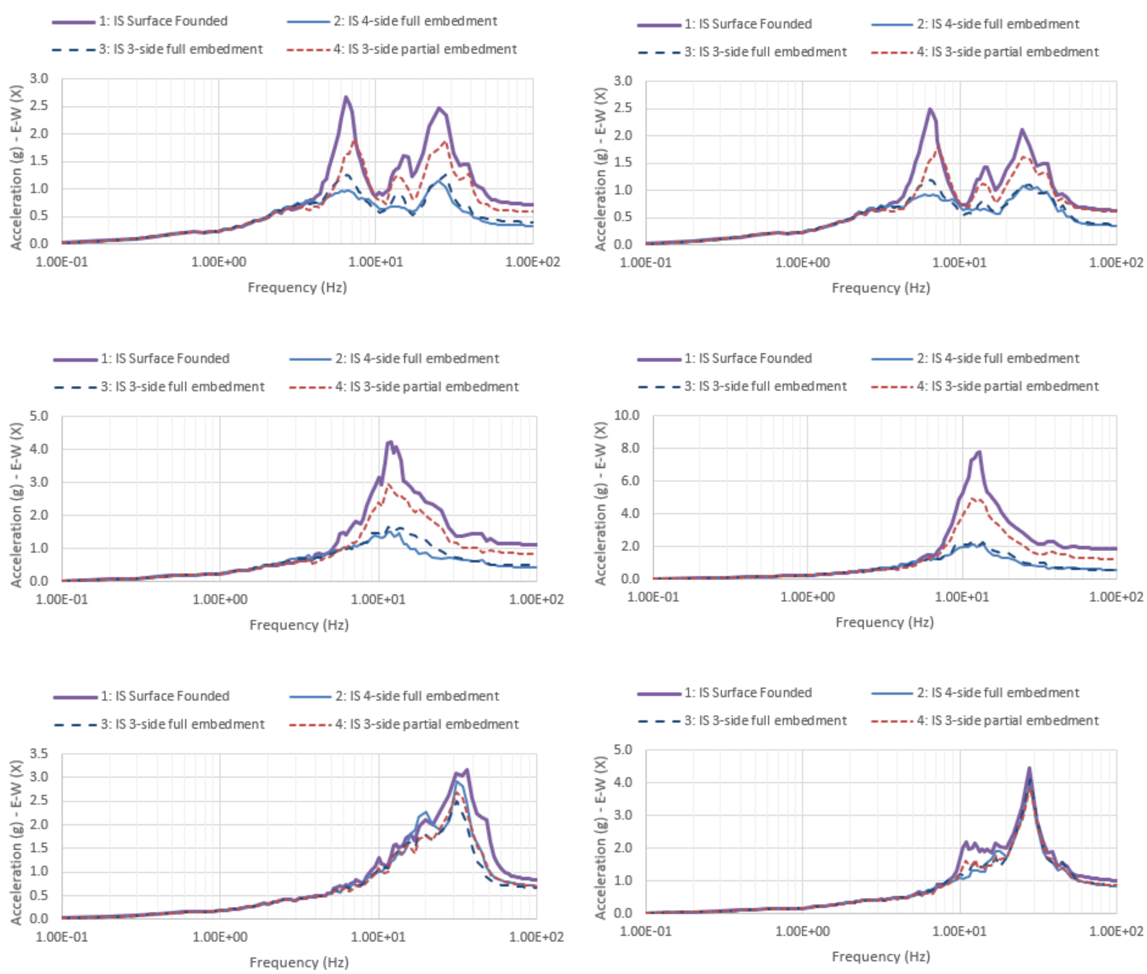


Figure 7: typical IS ISRS. left) node 2996, right) node 2023

CONCLUSION

This paper examined the seismic soil-structure interaction (SSI) response of two non-uniformly embedded structures as case studies. These structures were analysed via Finite Element (FE) modelling as part of seismic probabilistic risk assessment (SPRA) of a major NPP. For case study one, a system of three similar RBs, situated side by side, and booked by two smaller DGBs was investigated. Because of this configuration, while the three RBs in this study had similar structural configurations, each had a different embedment (either three-sided or two-sided embedment conditions) and/or SSSI condition. The goal of this study was to evaluate the feasibility of using a cost-efficient SSI model that included one RB only, since the inclusion of all five buildings in an extensive SSSI model was not computationally efficient. It was shown that, while ignoring the embedment did not produce realistic results, the use of a single RB SSI model that considered embedment on 2-sides of the building, while ignoring the DGBs and the corresponding third side embedment, produced ISRS results that were reasonably in agreement with the more complex model that included 3-side embedment and the smaller adjacent structure. For the case study two in which an IS was fully embedded across its height on three sides, the results indicated that, while ignoring the embedment completely on one hand, or the consideration of embedment as uniform on all four sides or even three sides on the other hand, did not produce realistic results, the treatment of the IS as partially embedded on 3-sides, with the top 20 ft. of embedment separated from the building, produced more realistic results than either surface founded or fully embedded cases considered in the study. In both case studies, it was possible to narrow down the range of responses away from the extreme cases that are typically considered because of the code or computational limitations.

The important conclusion drawn from the two case studies presented in this paper is that, in lieu of conducting SSI analysis on extensively large SSSI models on one extreme, or over simplification of non-uniform embedment as either no embedment or uniform embedment on the other extreme, the non-uniform embedment can be considered properly in many cases when using equivalent linear analysis tools, by conducting systematic sensitivity studies, which in turn can result in efficient and cost-effective solutions for idealizing such embedment conditions.

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