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Evaluating the effects on Structure-Soil-Structure Interaction in Commercial Nuclear Power Plants

Parthasarathy Chandran[1], Benny Jebuna Ratnagaran[1]

[1] Engineer, Risk Informed Engineering, Southern Company, AL, USA

ABSTRACT

After the Fukushima earthquake, the Nuclear Regulatory Commission had requested through the 50.54(f) letter, that all the utilities to assess the effects of ground motion response spectra at their site. This has created opportunities for seismic PRAs (SPRA) to be developed.

As part of the SPRA, it is essential to compute the in-structure response spectrum at SSCs location. Classical soil-structure interaction is used to compute the in-structure response spectrum, where the building with surrounding soil is modeled and evaluated. The effect of Structure-Soil-Structure Interaction (SSSI) on structural response of the nuclear power plant structures is not generally accounted for.

In this study, two sets of analyses are performed to demonstrate the influence of SSSI. Firstly, the SSSI effects between heavy buildings, which are separated by seismic gaps, are investigated. The buildings are analysed based on two models; independent considering the effect of Soil-Structure Interaction (SSI) alone and then including the surrounding structures. The response parameters such as transfer functions, stresses and response spectrum between these models are compared to assess the impact of SSSI.

Secondly, the SSSI effects on a lightly heavy building (e.g. Diesel Generator Building) due to the surrounding heavy buildings are examined. Initially, the analysis is performed by placing the lighter building at a distance very close to the heavy buildings and then the distance is increased linearly for each successive analysis. From the results, the influence of SSSI on the smaller building is quantified as a function of location relative to the large buildings.

INTRODUCTION

Following the accident at the Fukushima Dai-ichi nuclear power plant (NPP) resulting from the March 11, 2011, Great Tohoku Earthquake and subsequent tsunami, the Nuclear Regulatory Commission (NRC) issued a letter on March 12, 2012 NRC (2012). The letter requests that licensees and holders of construction permits under 10 CFR Part 50 re-evaluate the seismic hazards at their sites against present-day NRC requirements and guidance. A comparison between the re-evaluated seismic hazard and the design basis is performed, in accordance with the guidance published in EPRI's SPID (2013). If the comparison is concluded that the ground motion response spectrum (GMRS), which was developed based on the re-evaluated seismic hazard, exceeds the design basis seismic response spectrum in the 1 to 10 Hz range, and a seismic risk assessment is required. Typically, a seismic PRA (SPRA) has been developed to perform the seismic risk assessment in response to the 50.54(f) letter NRC (2012).

These seismic PRAs are performed to meet and peer reviewed against the ASME SPRA Standard (2013). The response analysis portion of the standard states the following: "When the design response analysis models are judged not to be realistic and state of the art, or when the design input ground motion is significantly different from the site-specific input motion, PERFORM new analysis to obtain realistic structural loads and floor response spectra". The word that is important and frequently missed by analysts is realistic.

The structures in nuclear power plants are often closely spaced and typically the SSI analysis is performed without the consideration of adjacent structures. The consideration of adjacent structures especially becomes important when the buildings are founded on soil sites. The dynamic effects that are typically seen are amplification in in-structure response spectra and dynamic soil pressure Christine Roy et al (2013), this is generally where the realism is missed. The goal of this paper is to identify when would it be imperative for an analyst to consider SSSI to obtain realistic structural loads and floor response spectra.

GENERAL PLANT DESCRIPTION

The nuclear power plant consists of two BWR NSSS units. For SS1, three structures are of interest--two reactor buildings, diesel generator building while turbine and control buildings are modelled as part of the analysis but are not assessed in this study. The reactor building is composed of a classic shear wall type building and bulb shaped drywell for the internal structure. The shear wall structure is a reinforced concrete structure with steel framing system on top. For this study, the internal structure includes both the drywell and a simplified stick model for the NSSS itself. These two structures interact through the foundation and star truss at the top of the drywell. The second structure, Diesel Generator Building, is founded at the plant grade while the reactor building is a deeply embedded structure. The diesel building (DB) is located around 100’ from the reactor-control-turbine (RCT) building complex. The buildings located within the RCT complex have a three-inch seismic gap between them. The plan including the buildings of interest is shown in Figure 1.

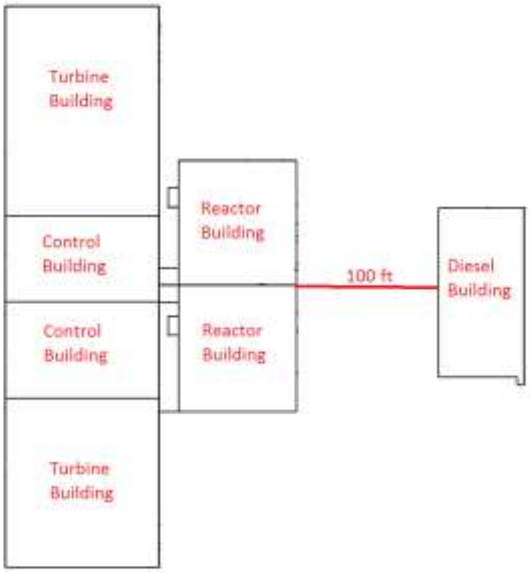


Figure 1. Plan for the nuclear power plant

NUMERICAL MODEL OF BUILDINGS

Superstructure

The 3-D Finite Element Models developed for this study was ensured to have an adequate number of discrete mass degrees of freedom to capture the global and local translational, rocking, and torsional responses of the structures. The element size was selected such that the dynamic response of the structure and the SSI effects will be adequately captured. The mesh size also ensures that the structures with full (uncracked concrete) stiffness properties could capture the local responses and responses of significant modes of vibration with frequencies equal to or below 30 Hz. For wave passage in the structure, to transmit shear waves with frequencies up to 30 Hz, the maximum element size shall not be greater than one fifth of the wave length to be transmitted SC-SASSI (2016).

The FEM was modeled “thick shell area” elements for modeling the walls, slabs, and steel liner; the “frame” elements are used to model the beams, columns, and the reactor pressure vessel (RPV); the “link elements” are used to model the crane, star truss, shear lug, drywell bellows seal, and refueling bellows seal; and the “solid” elements are used to model the drywell reinforced concrete section.

Structural walls are modeled as center-lined shell elements with their full un-cracked thickness for capturing the membrane and bending behavior. Slabs are modeled as center-lined shell elements with full un-cracked thickness for membrane and bending behavior. Concrete beams and columns are modeled as frame elements with un-cracked sections. Steel trusses, beams and columns are modeled as elastic frame elements.

SAP2000 (2015) was used to calculate the mass of the structure by application of shell, solid and frame element volume with a specified density. Thus, the mass is distributed throughout the structure. Seismic mass includes equipment loads, floor live load and misc. equipment load. The sample finite element model is shown for the reactor building in Figure 2.

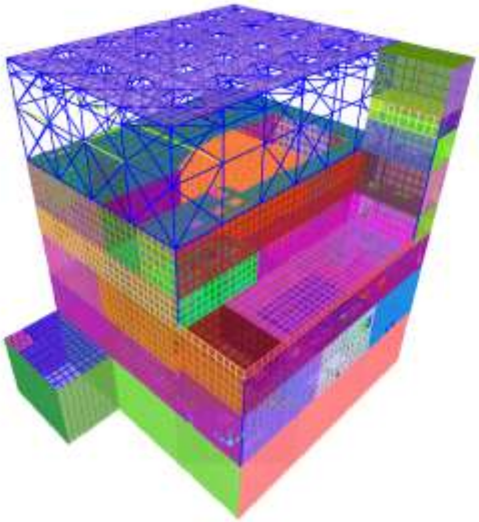


Figure 2. Schematic of the FEM Model

Foundation

The structural foundation and excavated soil block was generated separately using eight-node solid elements. High-stiffness springs were used for connecting the structure foundation to the superstructure. Instead of using classic approach of sharing the nodes between structure and excavated soil block at interfaces, structure and excavated soil block were connected using rigid links. High stiffness spring elements were used as the interacting agent between the excavated soil block and the structure. A maximum mesh size was based on the shear wave velocity of the underlying soil the foundation and the excavated soil model were interacting with. for mesh-refinement of the structure foundation elements. The criterion was identified in the SC-SASSI (2016), which states that the distance between two adjacent interaction nodes must not exceed one-fifth the wavelength at the highest frequency of analysis.

INPUT GROUND MOTIONS

Reactor Building Unit 1 and Unit 2 (Analysed as Embedded)

Five sets of acceleration histories (two horizontal components and one vertical component) are generated to match the target outcrop spectra at the soil column depth where the reactor building foundation is located. These acceleration histories are then used to obtain the in-column acceleration histories at the same foundation elevation. A total of fifteen acceleration time histories (2 x 5 = 10 for the horizontal direction and 1 x 5 = 5 for the vertical direction) are generated, corresponding to the best estimate soil profile as explained in the following section. Figure 3 presents the spectral shapes of the input motion in the horizontal direction for the reactor building analyses.

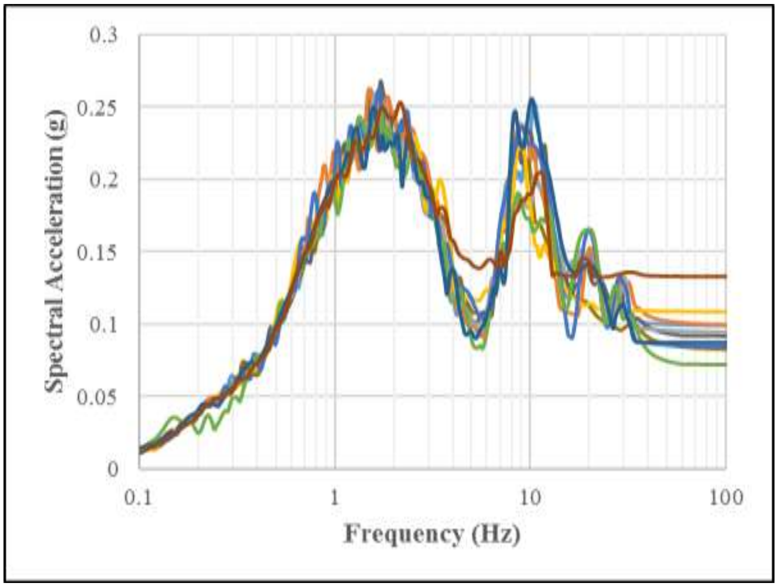


Figure 3. Spectral Shapes – Reactor Building Analyses

Diesel Building and RCT Complex (Analysed as Surface Founded)

One set of acceleration histories (two horizontal components and one vertical component) are generated to match the target spectra at the grade level. A total of three acceleration time histories (2 x 1 = 2 for the horizontal direction and 1 x 1 = 1 for the vertical direction) are generated. Figure 4 presents the spectral shapes of the input motion in the horizontal direction for the diesel building and RCT complex analyses.

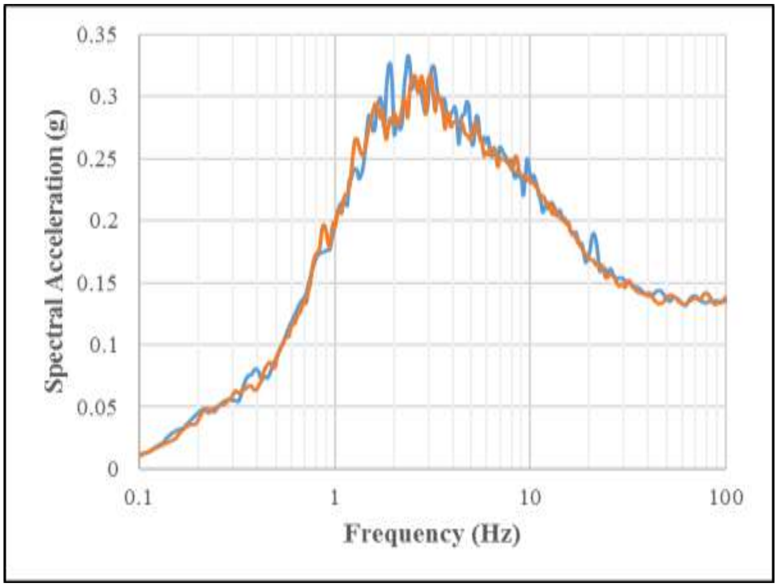


Figure 4. Spectral Shapes – Diesel Building and RCT Complex Analyses

SOIL PROFILE

The best estimate soil profile used for this study is presented in Figure 5. Their median strain-compatible properties, shear wave (Vs) and compression wave (Vp) velocities and corresponding hysteric damping values provide a representation of properties that address soil conditions for site. Soil layer thicknesses used in the analyses are refined to meet the SASSI criteria of minimum layer thickness for passing the cut-off frequency of 30 Hz. The cut off frequency of 30 Hz was based on the energy content of the input motion spectra. The energy content of the input motion spectra completely fades at frequencies above 30Hz.

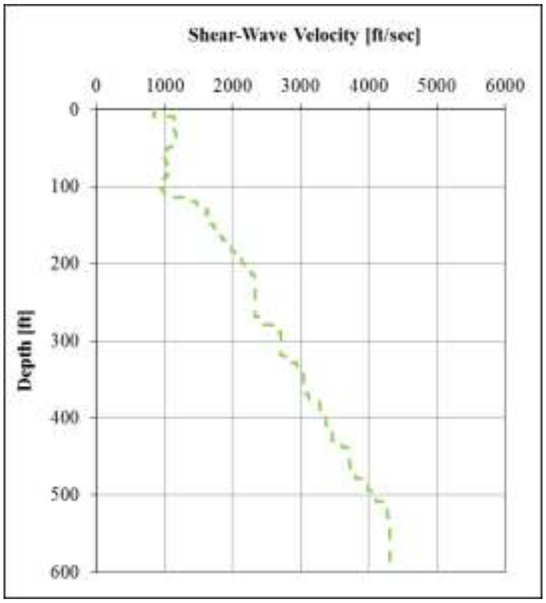


Figure 5. Shear-Wave Velocity Vs Depth

SOIL-STRUCTURE INTERACTION (SSI) ANALYSES

Reactor Building (Analysed as Embedded) / Diesel Building (Analysed as Surface Founded)

The SSI analysis for one of the reactor building is analysed as an embedded structure considering coherent seismic input. To perform SSI analysis, structure foundation and the excavated soil block are added to the initial fixed-base FEM. Sensitivity studies are conducted to ensure there is satisfactory alignment between the two models. The SSI analysis for the diesel building is analysed as a surface founded structure considering coherent seismic input.

STRUCTURE-SOIL-STRUCTURE INTERACTION (SSSI) ANALYSES

The SSSI analyses are performed using SC-SASSI (2016) for the following cases:

- Reactor Building Unit 1 and 2 (Analysed as Embedded)
  - SSSI effects between heavy buildings are investigated.
- Diesel Building and RCT Complex (Analysed as Surface Founded)
  - SSSI effects on a lightly heavy building (e.g. Diesel Generator Building) due to the surrounding heavy buildings are examined.

Reactor Building Unit 1 and Unit 2 (Analysed as Embedded)

The reactor building unit 1 SSI model is mirrored to obtain the reactor building unit 1 and 2 SSSI model along with the seismic gap. The seismic gap is filled with the excavated soil elements, to represent the absence of soil between the buildings. The overall superstructure and the excavated soil block for the SSSI analysis is shown in Figures 6 and 7. The SSSI analysis of the Reactor Building Unit 1 and 2 at Hatch Units 1&2 could not utilize the Direct Method due to the excessively large size of the embedded part of the structure. Instead, the Extended Subtraction Method (ESM) described in SASSI2010 User's Manual (2012) was used.

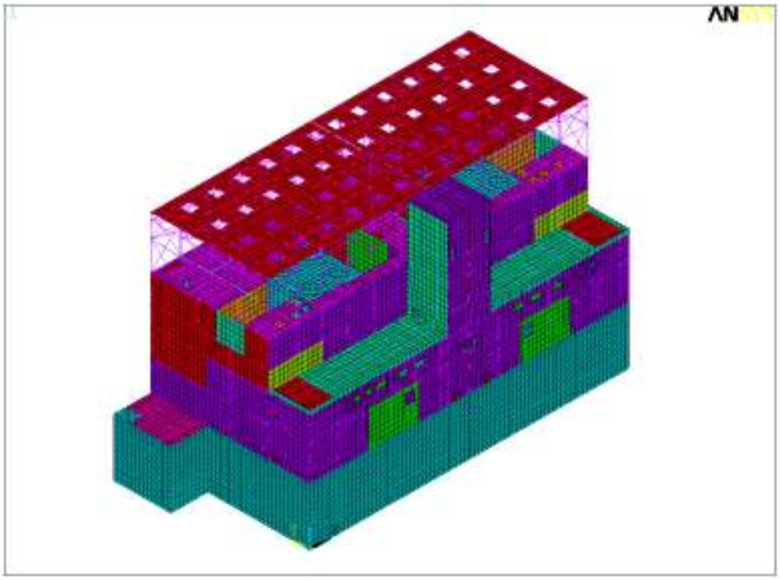


Figure 6. SSSI Model – Reactor Building Unit 1 and 2

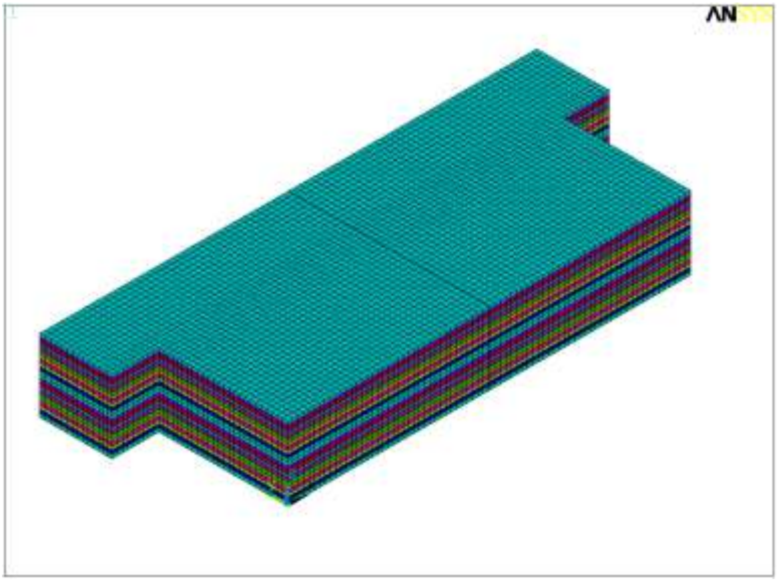


Figure 7. SSSI Model Excavated Soil Block– Reactor Building Unit 1 and 2

Diesel Building and RCT Complex (Analysed as Surface Founded)

The RCT complex comprises of the reactor building, turbine building, and control building. The diesel building is located about 100' from the RCT complex. The SSSI analysis for this configurated is performed by placing the diesel building at a distance one feet close to the RCT complex and then at increasing distance, including the actual 100' distance, for each successive analysis. Additionally, free field modes are placed at various distances from the RCT complex and the responses are extracted. The overall superstructure for the SSSI analysis is shown in Figure 8. The SSSI analysis of the diesel building and the RCT complex utilize the Direct Method.

RESPONSE COMPARISON

Reactor Building Unit 1 and Unit 2

With two buildings that are similar in weight and stiffness properties, it is expected that the dynamic properties of the reactor building would not be influenced. After careful examination of the transfer functions and based on Figure 9, it is clear the response values is strongly influenced by the presence of the adjacent unit. Even though the variation may only be shown to be around 15%, it may be concluded that the comparatively heavy buildings has strong influence on the dynamic response analysis based on the stiffness of the underlying soil material.

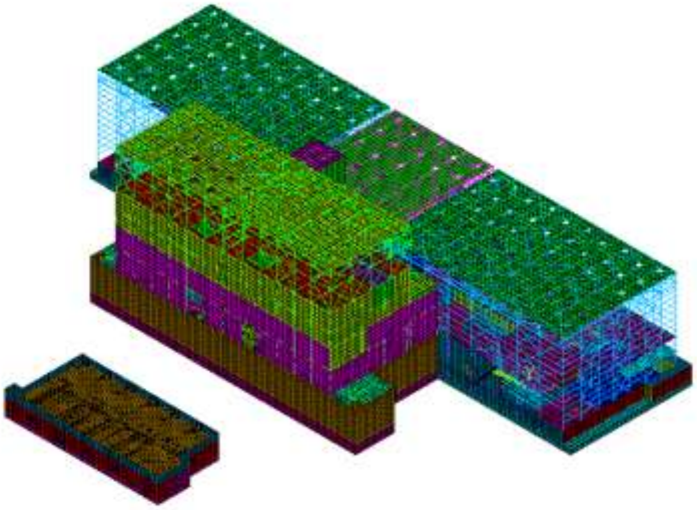
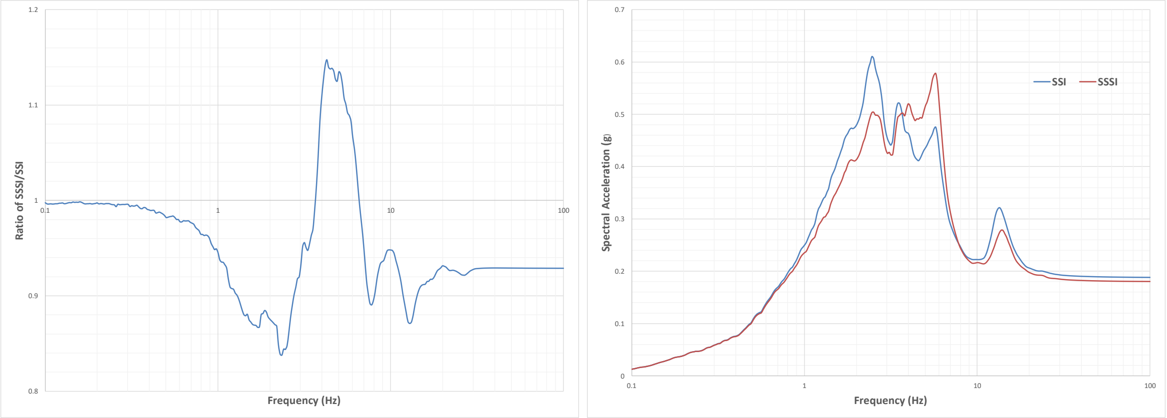


Figure 8. SSSI Model – Diesel Building and the RCT Complex

Diesel Building and RCT Complex

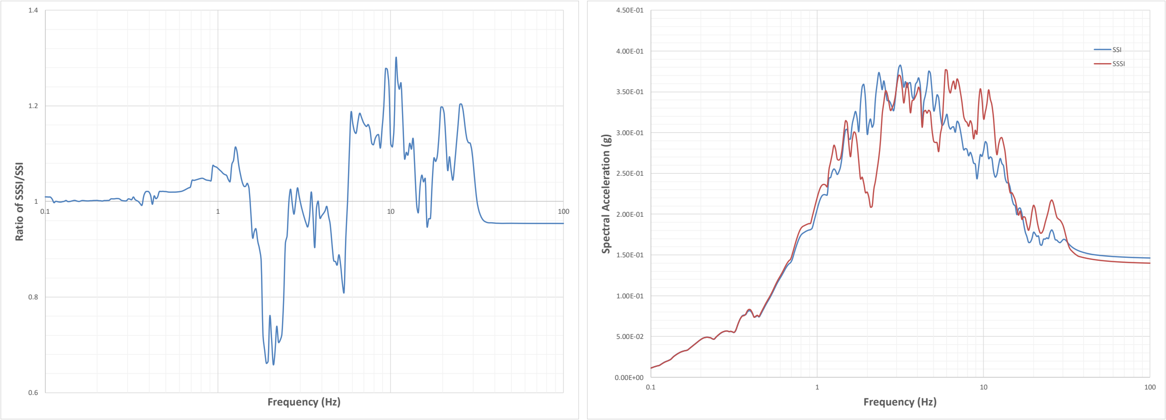
The effect of the SSSI on the response of the diesel building was assessed by comparing the results of the analysis with and without the interaction between the RCT complex. The results show more than 20% change response at the soil column frequency which clear shows the effect of SSSI as plotted in Figure 10. The effect of SSSI on the diesel building can be considered substantial. The distance up to which a heavy and large footprint building/complex would influence the ISRS of smaller inertial mass building is analysed in detail in the next section.



a) Ratio of SSSI to SSI

b) Representative ISRS

Figure 9. ISRS Comparison – Reactor Building – Top of the Structure – Along the Direction of the Adjacent Unit

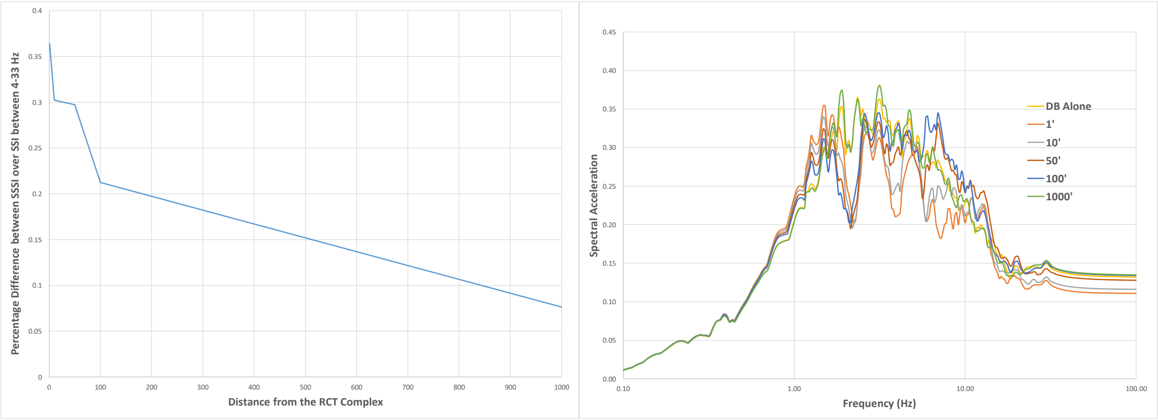


a) Ratio of SSSI to SSI b) Representative ISRS

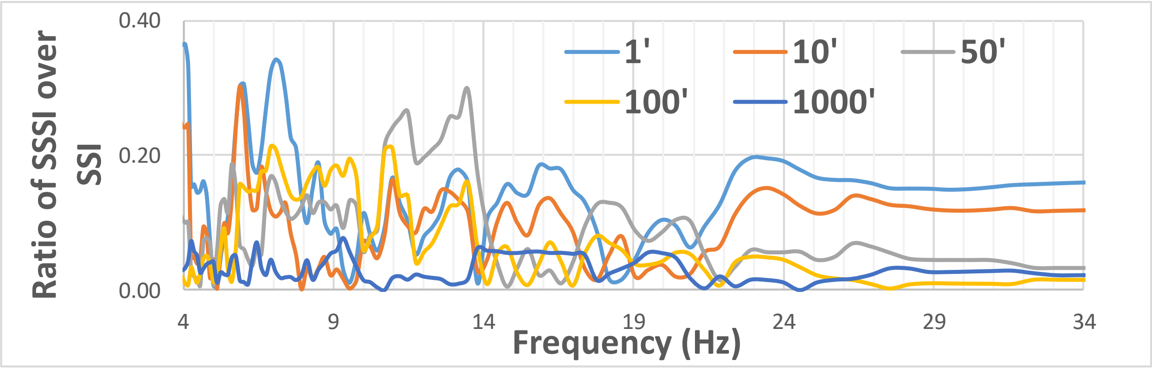
Figure 10. ISRS Comparison – Diesel Building – Top of the Structure – Along the Direction of the RCT Complex

Diesel Building as a Function of Distance from RCT Complex

This part of the paper is striving to identify the conditions at which SSSI should be considered and would have significant influence on the dynamic response on a structure. This was evaluated by placing the diesel building at a varying distance from 1ft to 1000ft, from the RCT complex, to simulate a



a) % Difference in ISRS between SSSI and SSI, Range 4-33 Hz b) ISRS



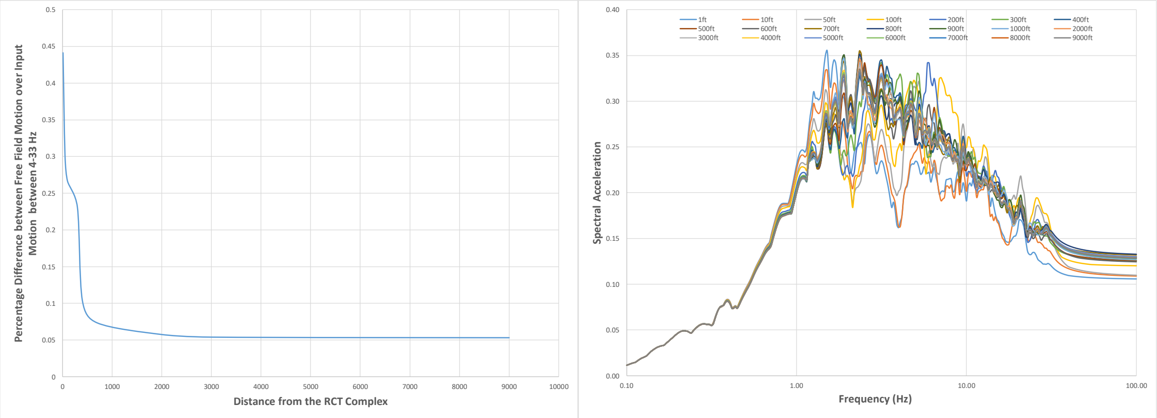
c) Ratio of SSSI to SSI, Range 4-33 Hz (DB located at various distances from the RCT Complex)

Figure 11. ISRS Comparison – Diesel Building – Bottom of Foundation

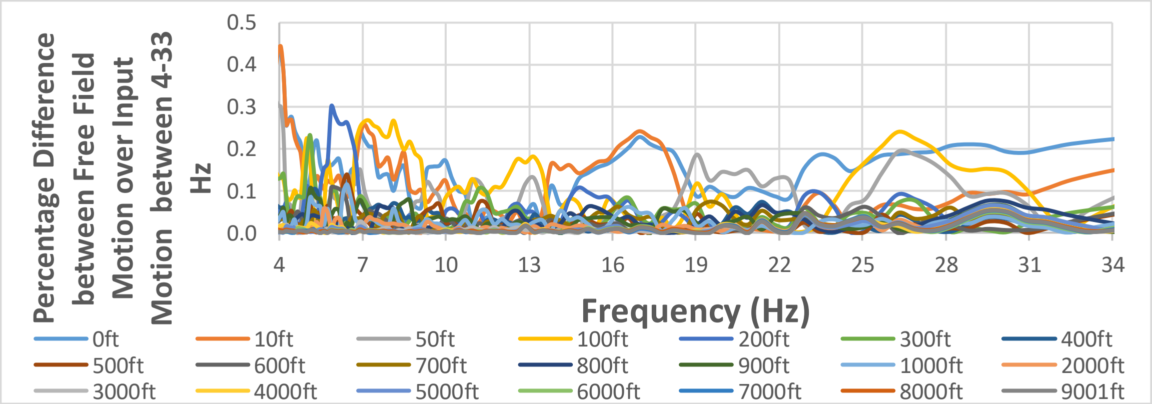
variable set of conditions. Figure 11 shows the results that were extracted from the analysis. The bottom of the diesel building foundation was chosen as the location of interest. The response was compared from these varying cases with the SSI analysis case for the diesel building and it can be seen in Figure 11a that after around 100ft the difference in response drops off steeply. Then a frequency range of interest is introduced based on the typical equipment in NPPs and chosen to be 4 to 33hz, to cover both electrical and mechanical equipment. It can be seen in Figure 11c that only when the building about 50ft away from the RCT complex, there is a substantial influence.

Free Field Motion as a Function of Distance from RCT Complex

The free field part of this paper was done more as a curiosity exercise to see when does the free field converge to the input response spectra. For this exercise, free field nodes are placed on grade at a varying distance from a point near the RCT complex till 9000ft away from the RCT complex. As seen in the Figure 12a, there is a significant decrease at around 350ft and the free field motion starts converging towards the input motion. If a concept like the frequency range is applied to this problem, then it be concluded that free field motion would be significantly affected within a 100ft distance from the RCT complex. This helps towards deciding correlation of two similar SSCs, that there is a case to be made for them not to be totally correlated as it can be seen that there would at least be difference in the demand side which would need to be considered when they are near heavy footed building/complex like the one considered in this study.



a) % Difference in Response Spectra between Free Field Nodes located at various distances from the RCT Complex and the Input Motion, Range 4-33 Hz b) Response Spectra



c) Ratio of Response Spectra between Free Field Nodes and the Input Motion

Figure 12. Response Spectra Comparison – Free Field Node and Input Motion

CONCLUSION

A typical BWR type site was used to study the impact of heavy structures, heavy and light structures located at a distance from 1ft to 1000ft. Also, free field motion was monitored at distances up to 9000ft to verify the distance at which it would converge to the input motion. The study was performed for both surface and embedded structures with soft soil profiles. The SSSI responses in terms of in-structure response spectra were compared to corresponding responses from SSI analysis of the stand-alone structure. It is concluded that the comparatively heavy buildings have strong influence on the dynamic response analysis based on the stiffness of the underlying soil material. There is a significant change in response at the soil column frequency which clearly shows that the effect of the SSSI on the lighter surface founded building can be substantial from an embedded heavy building/complex. Based on the frequency range of interest for typical equipment in NPPs (4 to 33hz), it can be concluded that when a lighter building is about 50ft away from the RCT complex, there would be substantial influence. Finally, the paper evaluates when would it be imperative for the SPRA analyst to use a correlated input motion for structures located at the same elevation and when would it be important to look at a site-wide SSI analysis.

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