SEISMIC STRUCTURE-SOIL-STRUCTURE INTERACTION IN NUCLEAR POWER PLANT STRUCTURES

C. Bolisetti1, A. S. Whittaker2
1Graduate Student Researcher, CSEE Department, University at Buffalo, SUNY, Buffalo, NY, USA – 14260
2Professor and Chair, CSEE Department, University at Buffalo, SUNY, Buffalo, NY, USA – 14260
Correspondence to: C. Bolisetti (cb76@buffalo.edu)

ABSTRACT

Soil-structure interaction is integral to the seismic analysis and design of safety-related nuclear structures, but interaction between multiple structures supported on the same soil domain is generally ignored. It is unknown whether structure-soil-structure interaction (SSI) can lead to significant changes in the response of nuclear structures. The study described in this paper examines the influence of SSSI on the response of a pair of Nuclear Power Plant (NPP) structures by comparing their response with and without a neighboring structure. Both in-plane SSSI (structures aligned parallel to the direction of ground motion) and anti-plane SSSI (structures aligned perpendicular to the direction of ground motion) are considered. The analyses are performed using the industry-standard frequency-domain code, SASSI. Lumped mass models of the Advanced Candu Reactor (ACR) are used for the analyses. Frequency-domain transfer functions are calculated at various locations in the reactors for different separation distance and relative mass of the reactors. Seismic responses are compared to the benchmark case where only one reactor is analyzed. Three pairs of NPP structures are considered: 1) two standard reactors (ACR’s), 2) two heavy reactors with four times the mass of the standard reactor, and 3) a heavy ACR placed next to the standard reactor. Each pair is analyzed considering in-plane and anti-plane arrangements for three values of separation distance. Seismic analysis is performed for one of the cases and the acceleration responses of the reactors are presented for the El Centro ground motion input at the free field. On-going studies are extending the scope of the analysis to other ground motion records and site soil profiles to enable the authors to generalize results and develop recommendations for analysis and design of nuclear structures.

INTRODUCTION

The phenomenon of soil-structure interaction has been studied extensively, especially for nuclear power plants (NPP’s). Analytical and numerical studies have been performed on individual NPPs installed over soil columns. However interaction between adjacent structures through their common soil domain, termed structure-soil-structure interaction (SSSI) here, has received much less attention. Most safety-related nuclear structures are designed with considerations of soil-structure-interaction (SSI) and SSSI is not considered. It is unknown whether the practice of ignoring SSI is conservative or nonconservative in terms of seismic demands on structures, systems and components.

A seminal study by Luco and Contesse [1] on SSSI examined anti-plane interaction between two infinitely long shear walls subjected to vertically incident SH waves of harmonic time-dependence. Wong and Trifunac [2] extended this study to an array of several structures with varying size and stiffness subjected to a shear wave incident at an arbitrary angle. Both of these analytical studies considered the significance of parameters such as separation distance, foundation size, and stiffness of the structures on SSSI. Luco and Contesse [1] identified the factors that determine the degree of interaction between structures as a) relative foundation sizes, b) the distance between the structures, c) the mass of the superstructure relative to the mass of the soil excavated for the foundation, d) mass of the foundation relative to the mass of excavated soil, and e) relative stiffness of the structures and the soil. Parametric analyses were performed and it was concluded that SSSI effects are especially important for smaller and lighter structures situated close to heavier structures. A similar conclusion was drawn by Wong and Trifunac [2]. Both studies noted that the degree of interaction depends mainly on the type of wave interference (constructive or destructive) occurring between the scattered waves from the foundations, which is a function of the spacing and arrangement of the foundations.

The primary objective of the study described in this paper is to examine the effects of 1) separation distance, 2) relative mass of reactors, and 3) the frequency of excitation, on the magnitude of SSSI between a pair of nuclear reactors. Numerical parametric analyses are performed to examine and understand the nature of this interaction. Two reactor masses are considered: standard and heavy. Three analysis cases are considered, each with a different pair of nuclear reactors: 1) two standard reactors, 2) two heavy reactors, and 3) a heavy reactor constructed...
near a standard reactor. Each of these cases is analyzed for both in-plane and anti-plane interaction (Figure 1), and multiple values of separation distance are considered. Frequency-dependent transfer functions are sought at important locations in the reactors and are compared with corresponding transfer functions calculated for the same reactors constructed alone. The seismic response for the 1940 El Centro ground motion is calculated for one of these cases and compared to the case where there is only one reactor. Results for more parametric analyses and responses for other ground motions will be reported in Bolisetti [3].

NUMERICAL MODELING

The equivalent-linear frequency-domain program, SASSI [4] is used for the numerical SSI analyses. In this program, the soil medium is represented by a semi-infinite halfspace composed of horizontal layers, and the structure is modeled using finite elements. The ground motion is specified at one of the layer interfaces as a combination of S-, P- and surface wave fields. In this study a vertically propagating SV-wave field is specified, which induces displacements in the X direction (Figure 1). The interaction forces on the foundation are calculated using the substructuring method [5] and the forces in the structure are then calculated using finite element analysis. The substructure subtraction method [5], which is a type of substructuring, is used for the analyses described here.

A lumped-mass stick model of the ACR-700 (Advanced Candu Reactor) reactor building [6] is adopted in this study (Figure 1). The model, which was initially developed by Huang et al. [7], for studies of seismic isolation of nuclear structures, enables calculation of macro-level deformation and force demands on structure floor acceleration response spectra at important locations in the reactor building. This dynamic model accounts for the mass and stiffness characteristics of the structure, and major equipment in the building, and has the same key dynamic properties as the complete three-dimensional building. Huang et al. [7] provide details on the development of the simplified numerical model.

The superstructure consists of three sticks, two for the internal structure and one for the containment. These sticks are joined at the concrete mat foundation. The actual containment vessel is a steel-lined, 1.2m thick, 59.5m tall, vertical cylinder and a 1.0m thick hemispherical dome. The horizontal cross-section of the containment wall is an annulus with an inner diameter of 39.5m and an outer diameter of 41.9m. Three-dimensional beam elements are used to model the containment stick using equivalent section properties for the beams, and masses are lumped at 12 nodes along the height. The internal structure of the reactor building consists of reinforced concrete shear walls and floor slabs that support the equipment and systems of the power plant. Its numerical model is approximately
symmetric about two vertical planes, and consists of masses lumped at 16 nodes. The reactor building is supported on a circular reinforced concrete foundation with a thickness of 2.5m, and a radius (r) of 20.95m. For the SASSI analyses described here, the foundation is shallowly embedded, and its thickness is reduced to 2m to make the foundation lighter and magnify interaction effects. Analysis case 1 uses the standard reactor building described above. The heavy version of the same reactor building used in analysis cases 2 and 3 is created by increasing the mass of the foundation and superstructure of the standard reactor building by a factor of four, and keeping the geometry of the structure unchanged. The heavy model is herein referred to as the modified reactor building.

A 31m deep linear elastic soil domain with an S-wave velocity of 600 m/s and P-wave velocity of 1200 m/s is considered for the analysis. The soil profile is modeled in SASSI using 14 horizontal layers overlying bedrock, with control ground motion specified on the topmost layer in the free field. Preliminary linear elastic ground response analysis in SASSI indicated that the soil column has a natural frequency of 5 Hz.

Separate analysis of the two reactor buildings embedded in the soil column described above was performed using SASSI. The computed natural frequencies are summarized in Table 1. For reference, the natural frequencies of the containment vessel and internal structure of the standard reactor installed on a fixed (rigid) base are 4.5 Hz and 6.7 Hz, respectively. A damping ratio of 0.05 is used for the superstructure and soil in all subsequent analyses.

Table 1: Translational and rocking frequencies (Hz) of the reactor buildings considered in this study

<table>
<thead>
<tr>
<th></th>
<th>Standard reactor building</th>
<th>Modified reactor building</th>
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<tbody>
<tr>
<td></td>
<td>Containment</td>
<td>Internal Structure</td>
</tr>
<tr>
<td>( f_{f1}^1 ) (translational mode)</td>
<td>4.5</td>
<td>6.7</td>
</tr>
<tr>
<td>( f_{f1}^2 ) (translational mode)</td>
<td>14.2</td>
<td>14.8</td>
</tr>
<tr>
<td>( f_{SSI}^1 ) (rocking mode)</td>
<td>2.6</td>
<td>2.6</td>
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</table>

**NUMERICAL ANALYSIS**

Frequency dependent transfer functions with respect to the input ground motion at the free field are calculated at two locations in the reactor buildings: 1) the center of the foundation immediately below the reactor vessel, and 2) the topmost node of the internal structure, which corresponds to the location of the maintenance crane and the main steam lines in the reactor building. Transfer functions for X-direction earthquake shaking only are examined in this study, where the transfer function is computed at each input frequency as the ratio of output response at a particular location to the ground motion input. The magnitude of the SSSI is assessed by the changes in the amplitudes of these transfer functions from those calculated for a single reactor building. The rocking mode is the fundamental mode of these reactors on the soil column.

**Case 1: Interaction between two identical standard reactor buildings**

Figures 2 and 3 present the acceleration transfer functions at the two locations noted above for analysis case 1. The solid line represents the transfer function for the single reactor and the dashed lines represent the transfer functions for multiple reactors on a common soil domain. Three values of center-to-center distance (a) are considered: 57m (a/r = 2.7), 114m (a/r = 5.4), and 171m (a/r = 8.2), where r is the radius of the foundation.

The greatest difference in the transfer functions at each control location is observed at the rocking frequency of the standard reactor building (= 2.6 Hz) in both the in-plane and anti-plane configurations. The increase or decrease in the amplification at a particular frequency is not monotonic with an increase in the distance between the reactors. Smaller differences are observed at the first translational periods of the containment vessel (= 4.5 Hz) and internal structure (= 6.7 Hz).

**Case 2: Interaction between two identical modified reactor buildings**

Figures 4 and 5 present transfer functions at the same locations for analysis case 2. As for case 1, the solid lines represent the transfer functions of a single reactor and the dashed lines represent transfer functions for multiple reactors. The case 1 values of separation distance are used again for analysis case 2. The SSSI effects are again prominent at the rocking frequency of the modified reactor building (= 1.2 Hz) and at higher frequencies at the foundation level. The change in response, SSI (1 reactor) to SSSI (2 reactors), from analysis case 1 (standard
reactors) to analysis case 2 (reactors with four-fold increase in mass) is generally small at both control locations. Of interest is the significant difference between the transfer functions for the anti-plane arrangements in Figure 2(a) and Figure 4(a) at frequencies greater than 2 Hz.

Figure 2: Transfer functions for foundation horizontal acceleration in the standard reactors (Case 1)

Figure 3: Transfer functions for internal structure horizontal acceleration in the standard reactors (Case 1)
Figure 4: Transfer functions for foundation horizontal acceleration in the modified reactors (Case 2)

Figure 5: Transfer functions for internal structure horizontal acceleration in the modified reactors (Case 2)

Case 3: Interaction between modified and standard reactor buildings
Figures 6 and 7 present the transfer functions calculated at the center of the foundation of the two reactors. Both anti-plane and in-plane arrangements are presented with results for single reactors. From these plots it is evident that the response of the lighter structure is more affected by SSSI than the heavier structure. In the lower frequencies, the effects are notable around 1.2 Hz, which is the rocking frequency of the modified ACR-700 reactor. The difference is greater for frequencies between 4 and 6 Hz, which is close to the natural frequency of the soil column (= 5 Hz).
Response to earthquake ground motion

Figure 8 compares the SSSI and stand-alone acceleration responses at the foundation of the standard reactor when the in-plane arrangement of case 3 is subjected to the NS component of the 1940 El Centro ground motion. This widely used ground motion has a peak ground acceleration of 0.32g, a strong motion duration of 30 seconds, and a peak 5-percent damped spectral demand of 0.94g at a period of 0.19 second. Figure 9 presents data for the top of the internal structure. The reactors in this analysis are centered 51.9m apart ($a/r = 2.5$); the transfer function is presented in Figure 7(a). Two-second windows of the responses are shown in the figures for clarity. The peak
acceleration responses calculated at the foundation differ by a maximum of approximately 20%, and those calculated at the top of the internal structure differ by a maximum of approximately 10%.

![Graph](image1)

**Figure 8:** Acceleration response calculated at the foundation of the standard reactor to the El Centro ground motion, when located at a clear distance of 10m from the modified reactor (Case 3)

![Graph](image2)

**Figure 9:** Acceleration response calculated at the top of the internal structure of the standard reactor to the El Centro ground motion, when located at a clear distance of 10m from the modified reactor (Case 3)

**CONCLUSIONS**

The following conclusions are offered based on the study described above:

1. SSSI effects are more pronounced at the rocking frequencies of the reactors.
2. The four-fold increase in mass of the standard reactor did not result in a significant change in the magnitude of the interaction between the structures for the same distance of separation. Significant changes are observed if the mass of only one of the two reactors is substantially different from the other, which confirms the observations made by Luco and Contesse [1] and Wong and Trifunac [2] using analytical simulations.
3. The changes in the transfer functions due to SSSI are not linear with increasing distance between the reactors. The magnitude of the SSSI is governed by the type of interference between the scattered waves reflected from the two foundations.
FUTURE WORK

Parametric analyses are being performed using other values of separation distance to better understand SSSI. The scope of the analysis effort is being expanded to include nonlinear time-domain codes such as LS-DYNA [8]. The authors consider this important because for very closely spaced structures the interaction may be dominated by direct force transfer through the soil. Secondary nonlinearities, such as failure of the soil around the foundations, might be important and are better captured by nonlinear analysis codes. Further, the nonlinear codes are better suited for the assessment of seismic performance for beyond design basis shaking, where nonlinear response of the superstructure is expected and highly nonlinear response of the soil is likely.

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REFERENCES