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EFFECTS OF PILE FOUNDATIONS ON STRUCTURE-SOIL-STRUCTURE INTERACTIONS

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ABSTRACT

The structures housing the nuclear reactors are usually partially or fully embedded in the ground, with foundations extending to competent subgrade materials. In contrast, many adjacent buildings may need to be founded at ground elevation and do not require embedment. Under certain soil conditions, these surface-founded buildings may be supported by deep foundations (e.g., piles, drilled shafts, piers, and caissons). Deep foundations can transfer the heavy loads from the structure to deeper, more stable soil layers or bedrock, making them ideal for sites with weak or highly variable surface soils. Although the effects of piles on the seismic response of pile-supported foundations have been studied in the past, their structure-soil-structure interaction (SSSI) impact on adjacent structures needs to be better understood. A key consideration is understanding how the SSSI effects on nearby partially embedded safety-related structures are affected by deep foundations like piles or caissons compared to alternative shallow foundations.

This study uses simplified dynamic analysis strategies to evaluate how caissons might influence SSSI effects on adjacent embedded structures. A case study is presented, where structures adjacent to a deeply embedded building are initially modeled as surface-founded, representing a standard plant design (i.e., baseline design intended for broad suitability across various site conditions). The caissons are then added to the foundations of adjacent structures, representing a site-specific design where shallow foundations would not be economical. The goal is to assess whether the site-specific pile/caisson design could amplify SSSI effects compared to the standard plant design. To this end, the dynamic compatibility of the piles with free-field soil is evaluated to determine their impact on the free-field site response. The approximate inertial soil-structure interaction (SSI) effects of the surface-supported foundation are then compared with an equivalent caisson-supported foundation to understand how much the caissons could alter soil response amplification compared to the surface-founded foundations. The stresses at the deeply embedded building wall are also assessed to understand the extent of dynamic soil pressure change when piles are used instead of surface foundations. The effects of potential adjustments to the pile design are also explored.

INTRODUCTION

The compact footprint of the plant design and the deep embedment of the safety-related buildings in some of the recent advanced reactor technologies make the interaction of the deeply embedded buildings with the surrounding structures potentially more significant than traditional nuclear plant structures. The deep or partially embedded safety-related buildings are usually founded on competent bedrock. However, many adjacent buildings must be founded at elevations closer to the ground level. As a result, under certain soil conditions, these structures may be supported by deep foundations, namely caissons. It is not atypical for standard plant designs to consider the structures adjacent to the safety-related embedded building as surface founded. This is because the stresses imposed on the embedded structure by the seismic motion of surface foundations are perceived to be higher than those imposed by pile foundations, as pile foundations tend to be more flexible. However, as this study shows, this assumption is not necessarily correct for every situation.

Through simplified analyses, this study aims to determine whether the structure-soil-structure interaction (SSSI) effects of adjacent piles on a safety-related embedded structure can be more significant than those of an adjacent surface foundation, for example, in the plant's standard design.

SEISMIC ANALYSES

For seismic soil-structure interaction (SSI) analyses, two different soil-foundation systems are considered (Figure 1): (I) a surface foundation with superstructure mass, and (II) a single caisson with superstructure mass. The surface foundation represents the foundation of a realistic, non-safety building. The single caisson represents only a part of the foundation, which is supported by a single caisson. For this simplified study, this is a reasonable assumption given the expectation of a stiff pier cap diaphragm and reasonable mass distribution across individual piers. Comparing the responses of Systems I and II enables examination of the caissons' combined kinematic-inertial interactions. The objective is to understand the SSI and SSSI effects of caissons by comparing the seismic responses of the two soil-foundation systems.

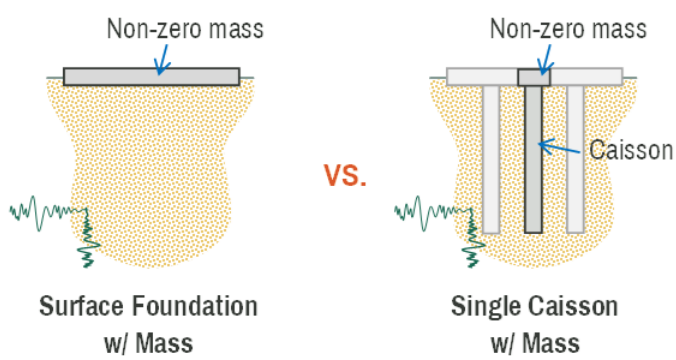


Figure 1. Considered soil-foundation systems for seismic analyses

The models are developed using the computer program SASSI (Ostadan (2007)). In support of the analyses performed via SASSI, the computer program LPile (Wang et al. (2022)) is used to characterize the caissons' near-field interaction with their surrounding medium. The surface foundation is modeled through a group of nearly rigid shell elements connected to the underlying soil via a grid of interaction nodes (Figure 2). In the single caisson model, the caisson is modeled through a series of massless three-dimensional (3D) viscoelastic beam elements connected to the interaction nodes via viscoelastic "p-y" spring elements (Figure 2). The interaction nodes and spring elements are placed at all the soil/rock layer interfaces along the caisson length. While using the interaction nodes would suffice to capture the far-field response of the soil, the p-y spring elements between the beam elements and the interaction nodes are necessary to capture each caisson's near-field/local interaction with the soil/rock in its immediate vicinity. Each p-y spring element is defined through stiffnesses and damping ratios corresponding to three translational degrees of freedom. The damping ratio of each p-y spring element equals the strain-compatible damping ratio of the soil/rock layer immediately below it. The p-y curves corresponding to each spring depth are obtained from LPile using an iterative approach described by Roy et al. (2015).

Description of the Model and Input Data

Figure 3 shows the representative dimensions of the caissons and the surface mat foundation. The examined caissons are assumed to have fixed heads. Figure 4 shows the properties of the four soil layers used in the SASSI analyses, and Table 1 lists the input properties for LPILE. The input motions are five sets of time histories (each set consisting of two horizontal and one vertical components) matched to the design response spectra at a site in the eastern United States. The average results obtained from each input set are used to compare the behaviors between the two models.

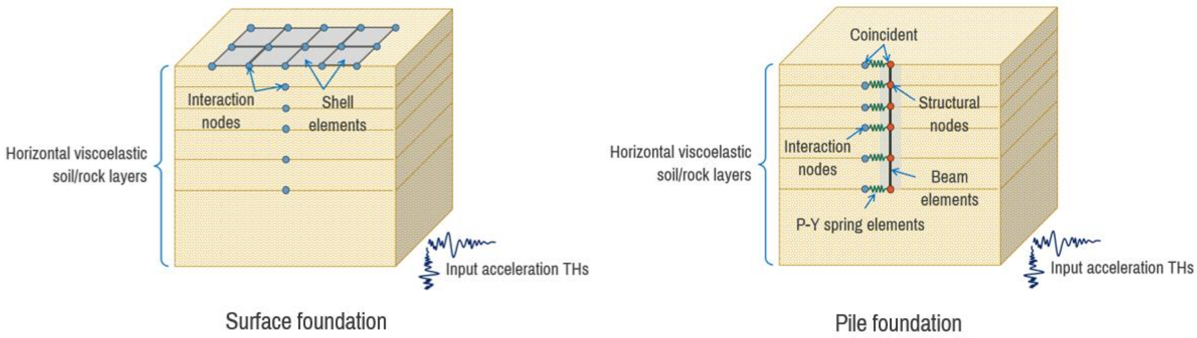


Figure 2. Schematic illustration of SASSI models for surface foundation and single caissons

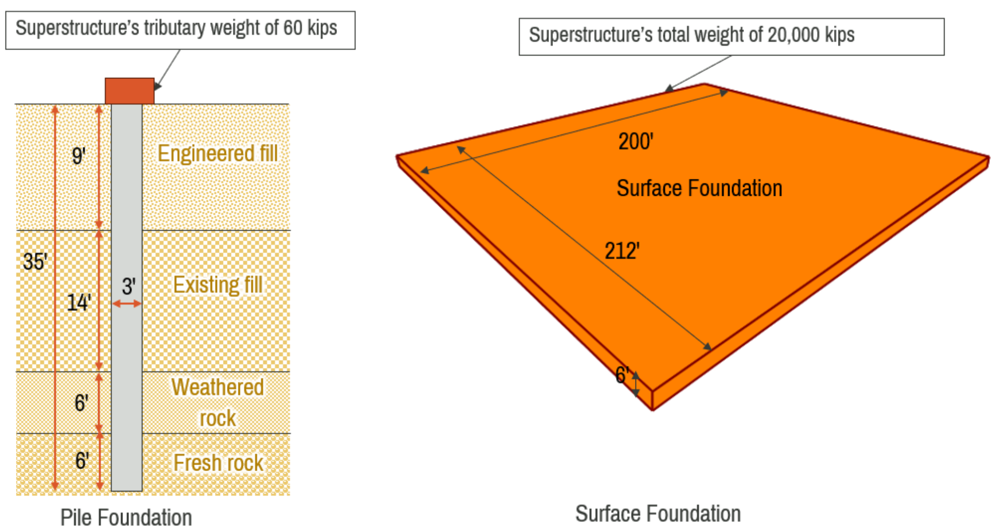


Figure 3. Soil layering and dimensions of the caisson and surface foundation considered in the study

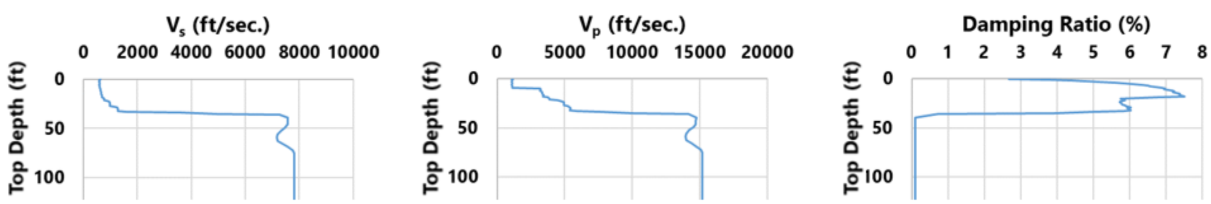


Figure 4. Strain-compatible dynamic properties

Table 1. Soil layer properties in the LPile model

p-y Curve Type	Parameter	Value
Sand (Reese)	Effective Unit Weight (lb/ft^3)	73
	Friction Angle (deg)	37
	Soil Modulus, k (lb/in.^{3})	262
Stiff Clay w/o Free Water	Effective Unit Weight (lb/ft^3)	58
	Undrained Cohesion (lb/ft^2)	1300
	Strain Factor E50	0.0078
Sand (Reese)	Effective Unit Weight (lb/ft^3)	78
	Friction Angle (deg)	37
	Soil Modulus, k (lb/in.^{3})	262
Vuggy Limestone	Effective Unit Weight (lb/ft^3)	168
	Compressive Strength, q_u (lb/in.^{2})	5000

Evaluation of Seismic Analysis Results

Figure 5 shows the maximum relative horizontal displacements (with respect to the free field at the input motion depth) of the interaction nodes in both Systems I and II and the caisson nodes in System II. Note that the displayed results are the averages of the seismic analysis results under all ten horizontal input motion time histories. The presence of the caisson insignificantly affects the subgrade displacement field. Figure 5 also compares the maximum shear strain profiles obtained from the seismic analyses of Systems I and II. As can be seen, the caisson's presence does not significantly increase the soil deformations, even though the caisson itself undergoes a large deformation. The maximum equivalent shear strain profiles show a reduction of the maximum subgrade shear strains near the surface (upper 5 ft) in the caisson presence. At depths below 5 ft, the maximum soil shear strain is relatively unaffected by the presence of caissons.

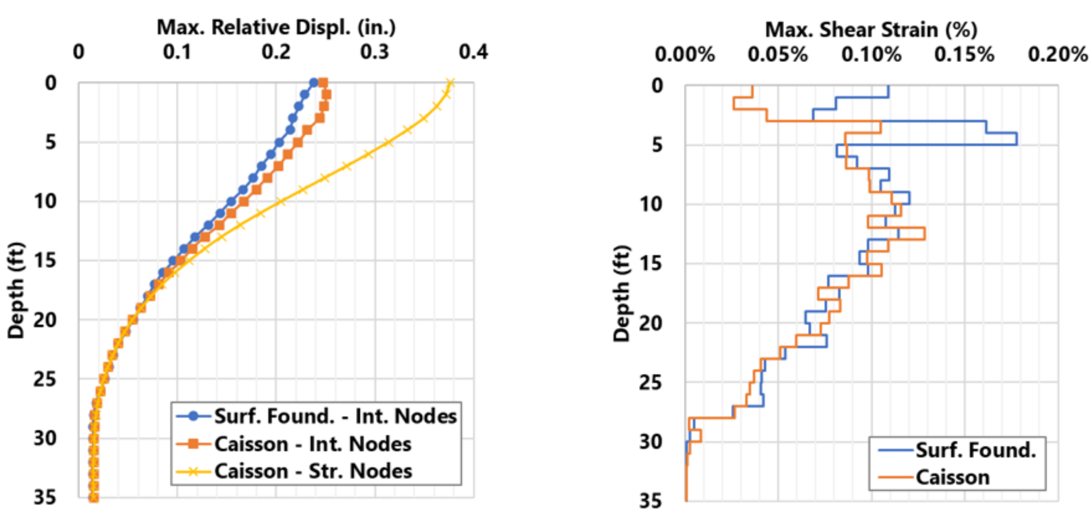


Figure 5. Maximum relative horizontal displacements and shear strains of subgrade layers

The 5%-damped horizontal and vertical acceleration response spectra for the same foundation nodes of Systems I and II (at grade level) are compared in Figure 6. Also shown in Figure 6 are the mean acceleration response spectra of the input motion time histories to allow their comparison with the foundation response spectra. As can be seen, the caisson's presence increases the peak horizontal spectral acceleration by ~100%, although the peak spectral accelerations beyond ~20 Hz are reduced. This is attributed to the caisson's ability to filter out the high-frequency waves moving toward the ground surface, which agrees with the literature (Di Laora and de Sanctis (2013); Turner et al. (2015)). In the vertical direction, the caisson's presence reduces the peak vertical spectral acceleration by 50%.

The above results indicate that caissons may not significantly affect the lateral displacements and shear deformations of their underlying soil/rock layers, particularly near the grade. However, they may intensify the supported foundation's horizontal displacement and acceleration responses.

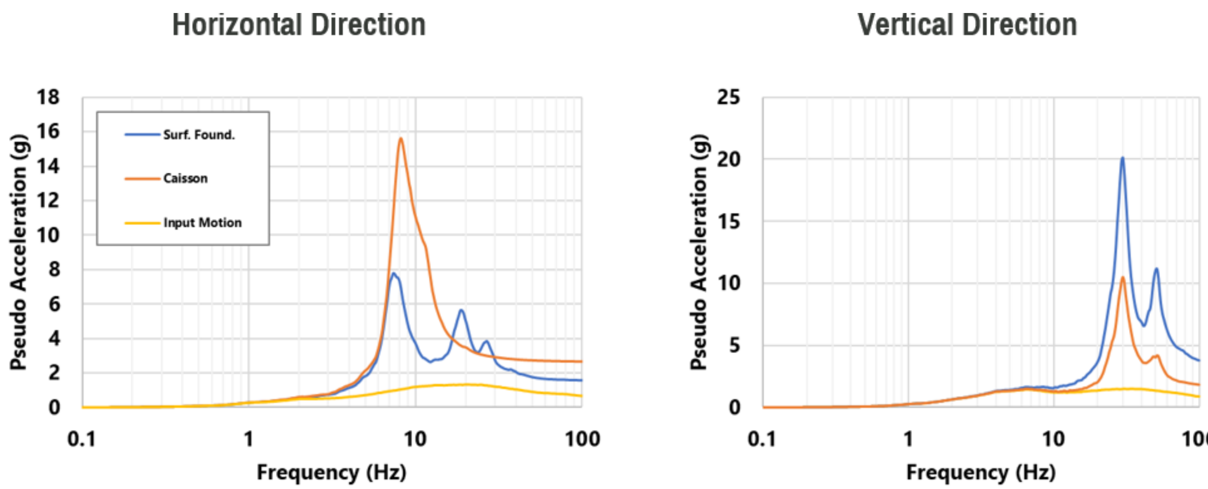
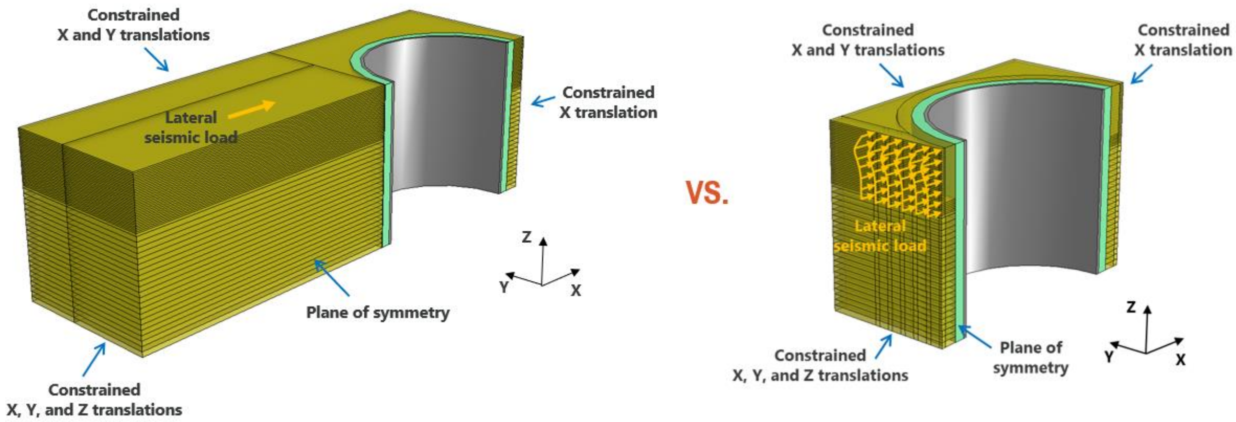


Figure 6. 5%-Damped acceleration response spectra at grade level

STATIC ANALYSES

The static analyses aim to examine how the caissons supporting the adjacent buildings affect the stress demands in the embedded structures due to SSSI effects. For this purpose, the stresses on the underground shaft due to representative lateral seismic force on the adjacent structure are evaluated under two scenarios: (a) a surface foundation supports the adjacent structure, and (b) caissons support the adjacent structure. The stresses induced on the embedded structure's outer shell under these two conditions are compared to predict whether the caissons may increase the seismic force demands of the embedded structure. The seismic reactions of the two foundation systems are estimated based on the seismic analysis results discussed in the previous section. ABAQUS (Dassault Systems (2023)) is used to create the 3D linear elastic finite element (FE) models of the above systems and analyze them under static loads. Figure 7 shows the two analysis models described above, and Figure 8 shows the structural configuration used in the static analyses to represent an embedded advanced reactor building.

The surface foundation's maximum seismic lateral load is the product of the representative superstructure mass based on the foundation's average horizontal zero period acceleration (ZPA) obtained from the seismic analyses of System I under all ten horizontal input motion time histories (Figure 6). The lateral seismic load from each caisson on its supporting soil/rock layers is calculated as the average of maximum absolute spring forces obtained from the seismic analyses of System II under all ten horizontal input motion time histories.



(a) (b)

Figure 7. FE models representing an embedded structure, the adjacent building foundation, and the interacting soil layers when (a) the adjacent building is surface-founded and (b) the adjacent building is founded on caissons

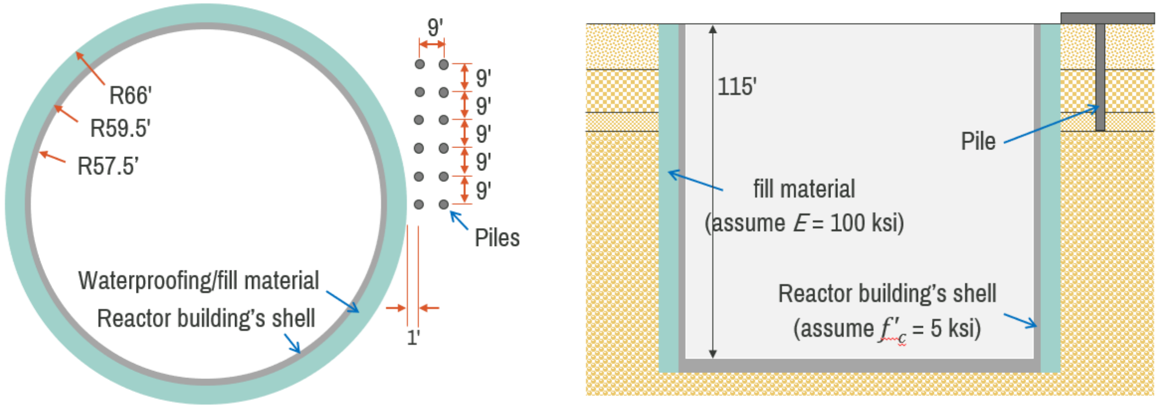


Figure 8. Structural configuration representing an embedded advanced reactor building

Evaluation of Static Analysis Results

To investigate the relative impacts of the adjacent structure's caissons vs. surface foundation on the force demands of the underground structure, Figure 9 compares the principal stresses induced in the underground structure's exterior shell. As can be seen, the maximum principal stresses caused by the caissons are ~70% higher than those by the surface foundation. This finding is attributed to the larger stress induced by the caissons into the soil (below the surface). In contrast, the surface foundation distributes the lateral seismic force demand over a larger area on the soil surface, reducing the resulting stresses. These results indicate the importance of the SSSI effects of piles.

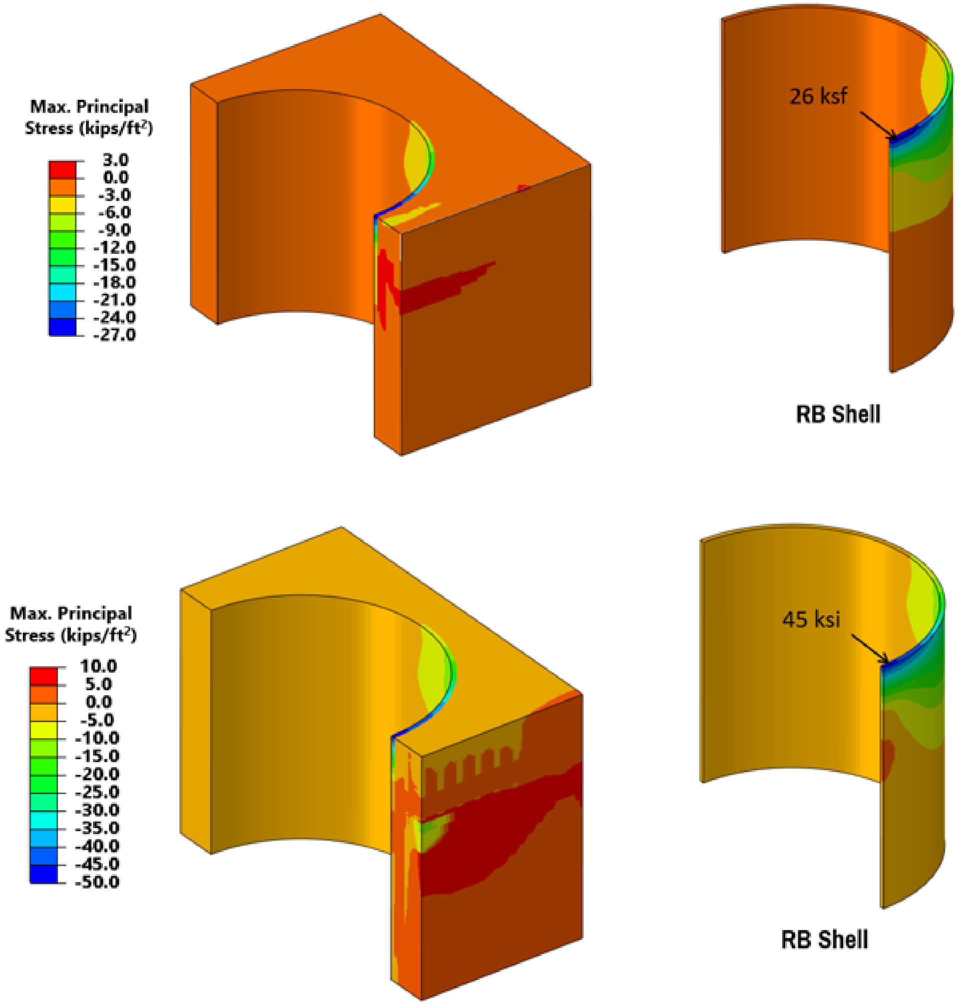


Figure 9. Principal stress in embedded structure due to seismic interaction with an adjacent structure when (top) the adjacent building is surface-founded and (bottom) the adjacent building is founded on caissons

EFFECTS OF CAISSON FLEXIBILITY

According to previous conclusions, using caissons in the foundations of the buildings adjacent to the underground structure could amplify their SSSI effects on the underground structure. The increased demands in the adjacent buildings and the underground structure in the presence of the caissons must be considered in the seismic design of those buildings. The caisson stiffness may be adjusted to alleviate/eliminate the above issues. This section explores the effects of stiffening the 3-ft-diameter caissons as a potentially beneficial adjustment. Specifically, two alternative cross-sections are examined, one 4 ft and the other 6 ft in diameter, while both have similar longitudinal rebar ratios to the current caissons. To explore the effects of these adjustments, each caisson is subjected to seismic analyses similar to those performed on System II (i.e., a single caisson with tributary superstructure mass). In these analyses, the tributary superstructure mass is kept the same to focus on the effects of caisson stiffening. The results of the new analyses are discussed below.

Analysis Results and Discussion

The foundation's horizontal and vertical acceleration response spectra for the same soil foundation systems examined earlier are compared in Figure 10. Both adjusted caisson stiffnesses substantially decrease the foundation's peak horizontal spectral acceleration with respect to the original caisson design. In the vertical direction, increasing the caisson stiffness increases the peak spectral acceleration at higher frequencies (> 40 Hz). Compared to the surface foundation, the 4 ft and 6 ft diameter caissons reduce the peak vertical spectral acceleration. This is because the stiffness increases of both caissons are enough to increase the vertical frequency of the soil-caisson system to the frequency range where the vertical input motions have lower energy contents.

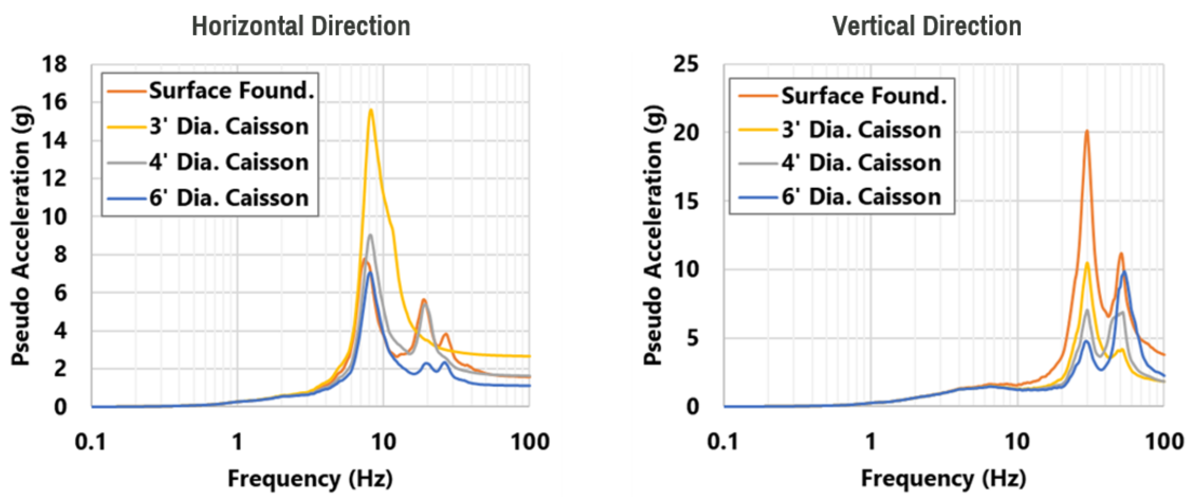


Figure 10. Caisson stiffness effects: (a) 5% damped horizontal acceleration response spectra; (b) 5% damped vertical acceleration response spectra

Figure 11 compares the relative displacement profiles of the subgrade and the caissons, along with the subgrade's equivalent shear strain profiles, all obtained from the seismic analyses of different soil foundation systems under horizontal excitation. Per Figure 11(a), the stiffer the caisson, the less the subgrade layers will displace compared to the surface foundation case. Comparing the subgrade displacement profiles of Figure 11(a) with the corresponding caisson displacement profiles of Figure 11(b) indicates the diminishing effect of the caisson stiffness on the local near-field deformations; the more flexible a caisson is, the more freedom it has to cut through its surrounding soil. Finally, the equivalent soil/rock layer shear strain profiles of Figure 11(b) show that, overall, even the adjusted caissons reduce the subgrade deformations compared to the surface foundation.

The foundation's horizontal displacement demands of the different soil foundation systems are compared in Figure 12. As expected from the earlier results, increasing the caisson diameter from 3 ft to 4 or 6 ft significantly decreases the foundation's horizontal displacement demands. The predicted displacement demands for the systems with the adjusted caissons are smaller than those for the surface foundation.

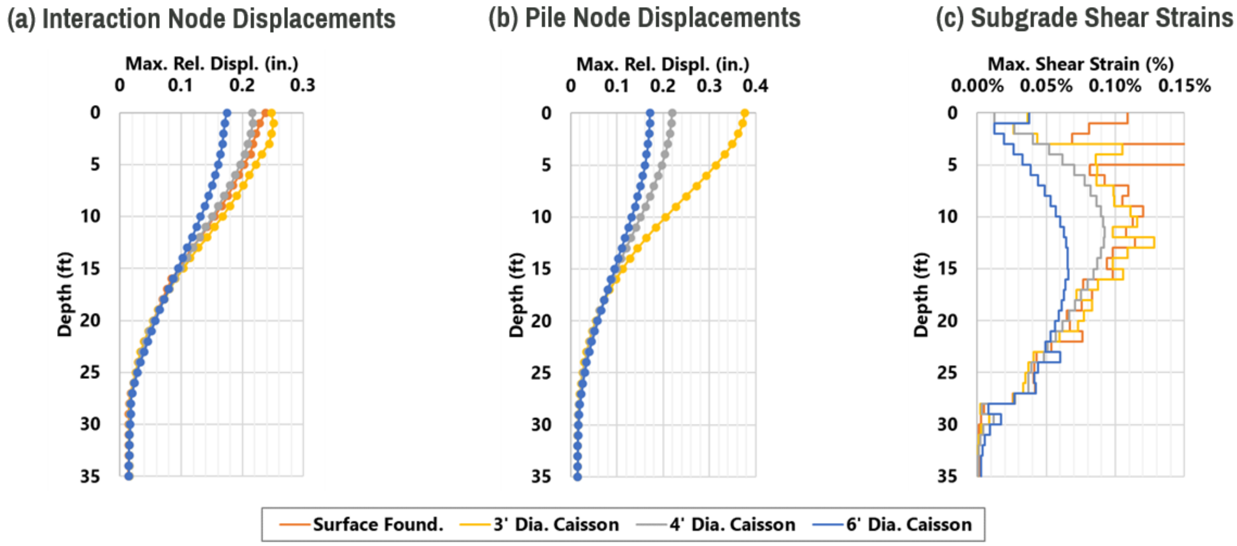


Figure 11. Caisson adjustment effects on subgrade deformations

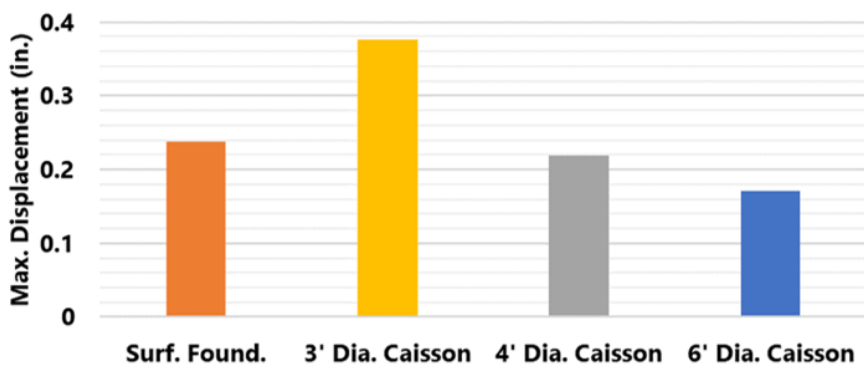


Figure 12. Caisson adjustment effects on maximum relative horizontal displacement

The above examinations indicate that increasing the stiffness of the caissons considered for the adjacent buildings by increasing their diameter can substantially reduce the horizontal acceleration response spectra, the horizontal displacement demands, and the maximum lateral loads on the foundations of those buildings. Additionally, the examined caisson adjustments were found to decrease the lateral subgrade deformations and maximum caisson reaction forces. Although not investigated in this study, increasing the number of caissons is another potential option to reduce the adjacent foundations' seismic displacement and acceleration response while maintaining the current caisson design.

CONCLUSIONS

This study investigated the potential SSSI effects of using caissons in the foundation systems of adjacent buildings on an embedded structure. Two sets of analyses on multiple soil foundation(-structure) systems were performed. The first set consisted of simplified seismic SSI analyses on two systems representing the adjacent structure's foundation system with surface foundation or caissons. This set of analyses aimed to examine how the caissons change the seismic response of the adjacent foundations, their subgrade displacements/deformations, and their seismic reactions on their supporting soil as indicators/predictors of SSSI effects on the embedded structure. The second analysis set consisted of simplified static stress analyses on two soil foundation structure systems to examine how caissons change the stresses induced by the foundation on the underground structure. Following the above analyses and based on their findings, possible adjustments to the caisson design were examined. The results of this study are suitable for qualitatively informing a design configuration. Primary conclusions and recommendations based on this study are as follows.

1. Adding caissons to the foundations of adjacent buildings can increase the horizontal acceleration responses at low frequencies and displacement demands of those foundations. This is attributed to the caissons' high flexibility and highlights the importance of considering the caissons' dynamic SSI effects in the seismic design of the buildings. On the contrary, the results indicate that caissons can reduce the peak horizontal and vertical accelerations at higher frequencies, which is beneficial for designing high-frequency sensitive equipment.

2. Compared to surface foundations, the results of this study indicate that caissons may increase the seismically induced subgrade displacements/deformations under the building foundations. This is due to (i) the caissons' ability to transfer the foundation's lateral seismic loads to the deeper soil layers and (ii) the accommodation of part of the caisson motions through local, near-field deformations of the soil near the caissons.

3. The pressures induced by the adjacent surface foundations on the outer walls of the underground structure were less than those otherwise induced by caissons. This is because the caissons could create larger localized stress, which can be transmitted to the embedded structure, whereas surface foundation force demands are distributed over a large area. Therefore, caissons may increase the associated SSSI effects under certain soil conditions or design configurations.

4. The results above depend heavily on the pile diameter/stiffness selection. Stiffening the caissons by increasing their diameter significantly reduced the acceleration and displacement responses of the supported foundations and decreased the seismic subgrade displacements/deformations.

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