Structure-Soil-Structure Interaction of Adjacent Buildings 
Subjected to Seismic Loading

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ABSTRACT:

The effects of soil-structure interaction (SSI) on the seismic response of different types of structures has been thoroughly investigated in the past 4 decades. Yet, the phenomenon of structure-soil-structure interaction (SSSI) was often overlooked. The present study aims at the rigorous investigation of the interacting effects of adjacent buildings in a two dimensional setting. The soil medium was assumed as a viscoelastic half-space modeled using plane strain finite elements. The aforementioned unbounded half-space is simulated utilizing the state-of-the-art perfectly matched layers implemented in the finite element method (FEM). The problem of the SSSI is solved in frequency domain. In order to fully model the stories below the ground level for the case of high-rise buildings, special modifications were considered for the interaction of the structure and the soil medium due to presence of spatially varying ground motion on the boundary of excavated region. The effect of different parameters such as foundation moduli and distance between adjacent buildings were investigated and the results were compared with models built using the conventional rigid foundation assumption. The results of the study showed that the interacting effects of adjacent building are prominent and need to be considered in the seismic design of buildings.

KEYWORDS: Adjacent buildings, Structure-soil-structure interaction, Perfectly matched layers, Frequency domain

1. INTRODUCTION

The problem of soil-structure interaction has been long studied for different types of structures. To tackle this problem, variety of numerical and analytical methodologies have been proposed during the last 4 decades. In this regard, the problem of a group of buildings in a dense area was addressed and the results showed that the SSSI effect can significantly alter the seismic response of adjacent structures depending on their distance and configuration (Padron et. al. 2009).

Finite element and boundary element methods has gain lots of interest especially following the great advancements in the computational power. Boundary element method (BEM) requires only a surface discretization and automatically accounts for the radiation condition without any need for using complicated non-reflecting boundaries as required by FEM. It was concluded that the boundary element method alone, or coupled with the finite element method, is ideally suited for dynamic soil-structure interaction problems from both the accuracy and efficiency viewpoints (Karabalis & Beskos, 1987). The use of BEM was also extensively investigated by the work of Chopra and his colleagues. More recently, the rigorous solution of the dam-foundation-reservoir interaction (DFRI) problem in a 3D setting was obtained in the homogeneous viscoelastic half space using a frequency domain boundary element procedure for canyons extending to infinity.

Although the accuracy and efficiency of the BEM were shown for a large number of problems, FEM has still its own advantages over BEM. Yet, using finite elements in modeling the soil medium in addition to the structure, leads to the major issue of proper simulation of wave radiation considering the soil medium was modeled as a bounded domain. One approach in modeling radiation damping of semi-infinite space, is the large scale modeling of the soil medium. This requirement demands a serious consumption of time and the internal memory
of a computer. Many studies have proposed various boundaries to reduce the above-mentioned scale such as the use of viscous boundaries (Lysmer & Kuhlemeyer, 1969). In addition to the development of the non-reflecting boundaries, the use of massless foundations was also considered. However, neither of these approaches shows acceptable level of accuracy.

In order to overcome the above-mentioned difficulties, the idea of a perfectly matched layer (PML) which is an absorbing layer model for linear wave equations that absorbs, almost perfectly, propagating waves of all non-tangential angles-of-incidence and of all non-zero frequencies, was first introduced in the context of electromagnetic waves (Bérenger, 1994). Later on, PMLs were formulated for the elastodynamic wave using complex-valued coordinate stretching functions to obtain the equations governing the PML (Harari & Albocher, 2006).

In the context of the discussion above, the main purpose of the present study is to investigate the interacting effects of adjacent buildings in a 2D setting. Using the FEM and PML techniques, the formulation allows modeling of multiple layers of soil stratum over half-space without dealing with the complexities of BEM. Including of the possibility of modeling excavated region, the approach is capable of modeling the kinematic SSI effects specifically important for the case of high-rise buildings where the structure can be embedded for tens of meters below the ground level. In addition, with the use of frame and shell elements, the structure is modeled without any approximation (as opposed to the case of single degree of freedom (SDOF) equivalent systems). The prominent factors studied throughout the research comprises of foundation material and distance between the building blocks. The study is arranged as follows. A short description of the frequency domain formulation is given in the next section. Then the accuracy of the formulation is verified using the analytical solutions. Afterwards, the frequency response functions are presented and the conclusions of the study are presented in the last section.

2. NUMERICAL MODELING

2.1. Finite element model of soil-structure interaction

Discretization of the soil medium was conducted using the linear triangular plane strain finite elements. The mesh size was chosen to accommodate at least 8 elements per wavelength of the highest frequency of interest. The finite element formulation of the domain was subjected to a slight modification for the easement of implementation of the PML elements. Nodal displacement compatibility matrix is given as shown in equation 1.

\[
B_a^T = \begin{bmatrix}
N_{a,x} & 0 & N_{a,y} & N_{a,y} \\
0 & N_{a,y} & N_{a,x} & -N_{a,x}
\end{bmatrix}
\]

In equation 1, N represents the FE shape functions where the first and second subscript are designated to the node number and the derivative direction, respectively. Utilizing the modified material property matrix (equation 2), stiffness matrix of the modified finite elements can be obtained using \(\int_{\Omega} B_a^T DB_b d\Omega\). In equation 2, the functions \(\psi_x\) and \(\psi_y\) are the complex valued frequency dependent stretch functions which have the value of unity over the bounded region leading to conventional mass and stiffness matrices. It should be noted that the aforementioned stretch functions are defined globally on the computational domain, not element-wise (Figure 1).
consistent mass matrix of the elements can also be determined using

\[ \int_{E} \rho N_{A}^{T} \psi_{x} \psi_{y} N_{b} d\Omega \]

where \( \rho \) denotes the mass density of the element. Detailed derivation of the formulations presented in this section is given in work of Harari and Albocher. In order to model the material damping, the complex-valued Lame parameters \( \lambda^{*} = \lambda(1+i\eta) \) and \( \mu^{*} = \mu(1+i\eta) \) are used in place of the counterpart real quantities \( \lambda \) and \( \mu \), \( \eta \) being the hysteretic damping ratio. The introduction of complex material property results in a complex-valued wave speed \( c^{*} = c(1+i\eta) \).

**Figure 1. Unbounded domain modeled using PML**

### 2.2. Equation of motion

The equation of motion for the structures in this study follows a modified version of the substructure method developed (Gutierrez & Chopra, 1978) and details in that regard can be found in (Bybordiani et al. 2017). Although a free-field uniform motion is assumed for the soil medium in the absence of structures, the employed substructure formulation allows for the inclusion of the spatially varying ground motions for embedded structures. This case is apparent where the soil medium is subjected to any level of excavation especially for the case of high-rise buildings. The governing equation in time domain for an elastic structure and foundation, is first transferred to frequency domain. It should be noted that the displacement fields in both of the substructures are partitioned into nodes on the interface and those located not on the interface in the following equations. The overbar denotes the frequency domain quantities.

\[
\begin{bmatrix}
L_{0}^{0} \\
U_{0}^{0}
\end{bmatrix} = 
\begin{bmatrix}
M_{ss} & M_{sb} & 0 \\
0 & M_{ff} & M_{bf}
\end{bmatrix}
\begin{bmatrix}
L_{U_{0}^{0}} \\
\bar{U}_{0}^{0}
\end{bmatrix}
\begin{bmatrix}
\tilde{K}_{bb}^{*} \\
K_{bb}^{*}
\end{bmatrix}
\begin{bmatrix}
0 \\
0
\end{bmatrix}
\]
In equation 3, the matrix \( LU^0_b = -K_{ss}^{-1}K_{sb}U^0_b \) represents the quasi-static displacement field in the degrees of freedom above the soil-structure interface due to free-field displacement in base degrees of freedom. It is clear that the only nonzero term on the right hand side of the equation 6, is the interacting forces. This fact can be understood considering that in the absence of the structure (i.e. free-filed state), there is not force on the foundation domain.

It should also be noted that \( \tilde{K}_{bb} = K_{bb} - K_{bs}K_{ss}^{-1}K_{sb} \) simulates the nonzero stiffness forces necessary to statically impose the displacement field \( \bar{U}^0_b \) over the interface (Gutierrez & Chopra, 1978). It should be noted that the implementation of material damping is conducted in the construction of element stiffness matrices in order to account for different hysteretic damping coefficients for different materials. Solution of equation 3 in frequency domain for discrete frequency points, can lead to the time domain responses of interest using inverse Fourier transform.

2.3. Effectiveness of PML boundaries

Verification of the FE and implemented PML approach are presented in this section. The results of the numerical model were compared to the analytical solution of a rigid strip-footing resting on a half-space. The foundation in this example has a width of 2b bonded to an elastic half-space (Figure 3.a). The half-space has a mass density \( \rho \), shear modulus \( G \), and a Poisson’s ratio \( \nu \). A dimensionless frequency \( a_0 = k_s b \) was defined where \( k_s \) represents the wave number for S wave. Constant strain finite elements were used in the discretization of FE as well as PML domain. It should also be mentioned that the PML domain is truncated using fixed boundary conditions. The vertical, horizontal and rocking harmonic forces and displacements of the footing are related through the dynamic flexibility matrix (equation 6).

\[
\begin{bmatrix}
F_v(a_0) \\
F_h(a_0) \\
F_{nh}(a_0)
\end{bmatrix}
\begin{bmatrix}
0 & 0 & F_v \\
0 & F_h & F_{hm}(a_0) \\
0 & F_{nh}(a_0) & F_{mm}(a_0)
\end{bmatrix}
\begin{bmatrix}
d_v \\
d_h \\
b d_0
\end{bmatrix} =
\begin{bmatrix}
F_v \\
F_h \\
M/b
\end{bmatrix}
\]

(4)

Considering the sensitivity of frequency domain solution to the frequency points’ step size over the lower range of frequencies, a logarithmic distribution of the aforementioned discrete points are preferred. The stretching functions are chosen based on the guidelines presented in (Harari & Albocher, 2006), with second degree polynomial attenuation functions in the PML region. Horizontal and vertical components of the dynamic flexibility coefficients computed for the elastic medium using PML model, are given in Figure 3.b and c against exact analytical counterparts.
In order to fully verify the accuracy and validity of the substructure approach specifically for the case of buildings embedded in the soil medium, a single building having 50 stories above and 4 stories below the ground level was modeled. The foundation material was chosen to have a shear wave velocity ($V_{s30}$) of 2000 m/s. Then models with higher Young’s Moduli for the soil medium were analyzed. Presented in Figure 4, is the frequency response function of the top floor displacement for different soil moduli as well as rigid a model embedded in a rigid soil domain. It is observed that the significant differences in the responses of systems resting on softer material tends to alleviate (and even disappear for the model with $V_{s30}=2000$ m/s) compared to the building on rigid soil.

Figure 3. Comparison of foundation flexibility obtained using PML approach and the analytical counterparts for a rigid foundation on half-space

Figure 4. Verification of the substructure method in presence of excavation
3. DEFINITION OF THE MODELS

For the parametric study of the addressed issue, different models were defined and simulated. Distance between the buildings and the soil stiffness being the prominent parameters affecting the interaction of the structures were investigated. For this purpose, three different soil shear wave velocities in the range of 200 up to 700 m/s in addition to structures built on rigid foundation are considered. Distance between the structures are chosen to be 5, 50, and 100 meters. It should also be noted that the soil domain was assumed to be comprised of a single material. The structures used in the present study are 15 story braced frames. The aforementioned steel structures were designed as per ASCE 7-10 and AISC considering the relevant seismic specifications. Given the two dimensional modeling of the soil-structure system, the foundation of these structures were modeled using beam elements. Lumped mass is assumed to obtain structural mass matrix and consequently the rotational inertial effects were neglected for the buildings.

4. FREQUENCY RESPONSE FUNCTIONS

Soil-structure interaction is the primary factor determining the seismic behavior of the structure-soil-structure systems. Given the prevalence of this issue on the problem, as well as the requirement of a frequency domain solution, frequency response functions can be used as an assessment tool for determining the behavior of buildings.

4.1. Effect of foundation stiffness

The frequency response functions for the three sets of building groups were obtained for different soil moduli. For a group of three neighboring buildings. The frequency response functions were evaluated at four different moduli. The soil was first treated as rigid, then assigned Young’s Moduli (E_s) of 3, 1.5, and 0.2 GPa in order to obtain V_s of 700, 500, and 200 m/s, respectively. The clear distance between the models was assumed to be equal to the height (50 m).

Investigation of the frequency response functions given in these figures shows that:

1) There was a significant difference in the natural frequency between the models built on flexible soil and the structures analyzed with rigid base assumption. This trend was valid even for a building resting on a soil profile having a shear wave velocity equal to 700 m/s. The difference in the fundamental frequency was valid for all ranges of the foundation Young’s moduli. However, the aforementioned difference was alleviated as the shear wave increased.
2) The maximum amplitudes correspond to the models with rigid foundation and the minimum response belongs to models with lowest soil stiffness.

3) The resonant amplitudes of the building with different foundation stiffness were also different. Yet, this phenomenon was more pronounced for the case of structures built on soft material. Known as the shielding action of outer buildings, the structures located in the middle region tend to experience lower amount of response compared to the outer counterparts.

4.2. Effect of distance

Distance between adjacent structures plays two important roles on their seismic response. Disturbed free-field motion due to the vibration of one buildings propagates in the soil medium with the highest amplitude for the corresponding to the fundamental frequency of the structure. These outward motions contribute to the motion of adjacent structures. The wave can increase or decrease the response of the neighbor building depending on the distance and the wavelength of the fundamental motion in soil medium. Yet, even without considering damping, the motion decays due to the two-dimensional radiation of waves. As a result, motions with higher wane-numbers tend to last more than those with higher wave-lengths; that is, high-rise structures with large periods cannot affect the adjacent structures as the low-rise structures do.

The distance between the structures were considered to be 5, 50, and 100 meters for the aforementioned set of structures, respectively, while keeping the shear wave velocity as 200 m/s. The chosen distances respectively represent building next to each other without considerable distance, structures having a distance equal to their height, and finally buildings having a distance two times their height. The frequency response functions were evaluated and results were compared for the aforementioned distances Figure 6.

Investigation of the frequency response functions reveals that unlike the effect of foundation stiffness, the clear distance between structures has a somewhat baffling effect on their response. First and foremost, as the clear distance increase from 5 to 100 meters, counterintuitively, the resonance response increases. This is a direct result of shear wave length depending on the frequency of interest as well as soil shear wave velocity. On the other hand, comparison of the results for buildings in different locations shows that there is not a clear trend between the corresponding responses.
5. CONCLUSION

In the present study, first a numerical model was developed in order to investigate the interacting effects of adjacent buildings. Implemented in the numerical approach was the state of the art, perfectly matched layers which facilitate the proper modeling of outward wave propagation in the FEM bounded domain. As a result, any approximations such as massless foundation modeling or inaccurate wave absorbing methods were prevented. Then two prominent factors affecting the dynamic response of structure-soil-structure interaction were investigated for a group of two dimensional steel braced frames. The following conclusions can be drawn based on the results of the analyses.

- There was a significant difference between the fundamental frequencies of structures built on flexible foundation compared to those modeled on a rigid foundation. This difference was considerable for the lower stiffness quantities as expected.
- For a given distance between structures, for all ranges of foundation flexibility, the outer structures in a group of buildings experienced higher responses compared to those located in the inner part.
- Unlike the case of foundation material property, the distance between structures plays a more sophisticated role in their dynamic response. It is well known that the wave length is dependent on the excitation frequency as well as shear wave velocity. Added to this alternating effect, is the decreasing amplitude of the outward waves even in the absence of material damping due to the loss of energy in 2/3D domains, further making the prediction of the resonant amplitude almost impossible.

The results of the analyses showed that the predictions from the rigid base assumption and rigorous SSSI analyses can be very different. This trend was valid for all range of systems. Given that there is substantial variability in the frequency content of earthquake motions, the difference in the fundamental frequency and resonant amplitudes play a considerable role in the dynamic response of groups of buildings. In conclusion, the seismic interacting effects of groups of buildings need to be considered.

REFERENCES


