BEM-FEM Coupling Model for the Analysis of Soil-Pile-Structure Interaction in the Frequency Domain

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Abstract. This communication presents a three-dimensional Boundary Element – Finite Element coupling model for the dynamic analysis of soil-pile-structure interaction in the frequency domain. The soil is modelled by the Boundary Element Method (BEM) and one-dimensional Finite Elements are used to model the piles as Bernoulli beams, whose heads can be linked by rigid pile caps. One or more superstructures can also be considered as piled shear building models, so that dynamic SSI problems can be addressed. Some structure-soil-structure interaction analyses are presented. It is shown that the presence of neighbouring structures with similar fundamental periods modifies the dynamic behaviour of buildings founded on soft to medium soils.

Introduction

The study of soil-structure interaction (SSI) has received considerable attention during the last decades [1, 2, 3, 4]. More recent [5] is the study of site-city interaction (SCI), focused on the influence of the presence of a densely urbanized area on the seismic response of zones placed inside or outside the city. SSI, site effects and structure-soil-structure interaction phenomena are the basic components of SCI. However, structure-soil-structure interaction, by itself, has received little attention, and even less work has been reported on the interaction between piled structures.

A three-dimensional BEM-FEM coupling model for the dynamic analysis of pile groups [6, 7] has been developed by the authors. The soil is modelled by the Boundary Element Method (BEM) [8] as a continuum, semi-infinite, isotropic, zoned homogeneous, linear, viscoelastic medium. The pile-soil interface tractions arising from the pile-soil interaction are regarded, from the integral equation point of view, as internal body forces. One-dimensional Finite Elements are used to model the piles as Bernoulli beams, whose heads can be linked by rigid pile caps. The code can take into account layered soils of generic stratigraphy and topography, including deposits and inclusions, and generic harmonic loads and incident seismic waves can be considered. Shear multi-storey piled structures can also be included in the model. Thus, the model can be used to obtain dynamic impedances and interaction factors of piled foundations and, under linear assumptions, the dynamic behaviour of complex soil-pile-structure systems can be studied rigorously with an affordable number of degrees of freedom.

This code has been used to study the structure-soil-structure interaction problem. Some results are presented here to show how the proximity of structures with similar fundamental periods modifies the dynamic behaviour of buildings and piles.

Problem Definition

All results presented herein correspond to one-storey shear buildings on a 3×3 fixed-head pile group embedded on a viscoelastic half-space. The geometric properties of building and piles are depicted in Fig. 1, where b = foundation halfwidth, L and d = length and sectional diameter of piles, s = centre-to-centre spacing between adjacent piles, h = structure effective height, m = structure effective mass, and m_o and I_o = cap mass and moment of inertia. The mechanical and geometrical properties of the piles and soil are defined by the following parameters: s/d = 5, pile/soil modulus ratio E_p/E_s = 1000, ratio between soil and pile densities ρ_s/ρ_p = 0.7, piles aspect ratio L/d = 15, soil damping coefficient β_s = 0.05 and Poisson ratio ν_s = 0.4. The structure is defined by: aspect ratio h/b = 2, 3 and 4; structure/soil mass ratio $m/4\rho b^2 h$ = 0.20; foundation/structure mass ratio m_o/m = 0.25; foundation mass moment of inertia I_o = 20m; structural damping ζ = 0.05; and structure/soil stiffness ratio $h/T{\cdot}c_s$ = 0.3, T being the fixed-base structure fundamental period and c_s the soil shear wave velocity. All figures are plotted against the dimensionless frequency $a_o = \omega d/c_s$, being ω the circular frequency.

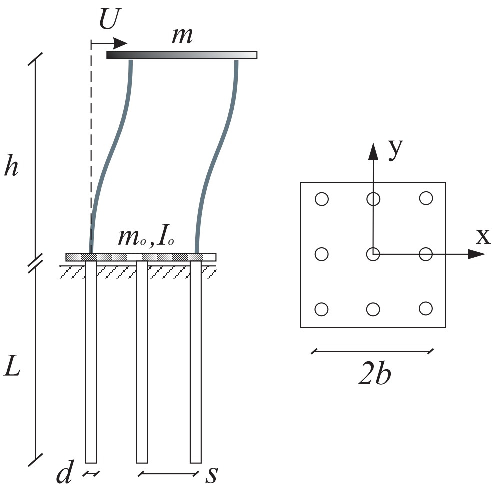

Fig. 1. Soil-pile-structure system.

Results

Fig. 2 presents the harmonic response spectra for structures of aspect ratio h/b 2 and 4 subject to vertically-incident SH waves, considered alone or in groups of three as depicted in the figure, with the slenderest structure in the middle and two other structures symmetrically placed at both sides. Two different separations between middle points of adjacent structures have been considered, as well as two different alignments: one along the same direction of the free field shaking due to the SH incident wave (the y axis) and another one along its perpendicular. The results are presented in terms of the spectral horizontal deformation $\Omega^2 u/(\omega^2 u_{ff})$, where Ω is the fundamental frequency of the fixed-base structure, u is the amplitude of the horizontal displacement of the top mass along the y axis relative to the foundation displacement and excluding rotations (*i.e.* the structural horizontal deformation), and u_{ff} is the amplitude of the free-field motion at the ground surface. It is worth noting here how the SSI effect becomes apparent in these cases, as the fixed-base dimensionless fundamental frequency of h/b 2 and 4 structures are 0.188 and 0.094 respectively, while the flexible-base fundamental frequencies are 0.155 and 0.074. However, the interaction between structures of non-similar fundamental frequencies exists but is negligible.

Fig. 3 presents the harmonic response spectra for structures of aspect ratio h/b 2, 3 and 4 subject to vertically-incident SH waves, considered alone or in groups of three *identical* structures with two different alignments as above, where it is shown that the interaction between structures of similar

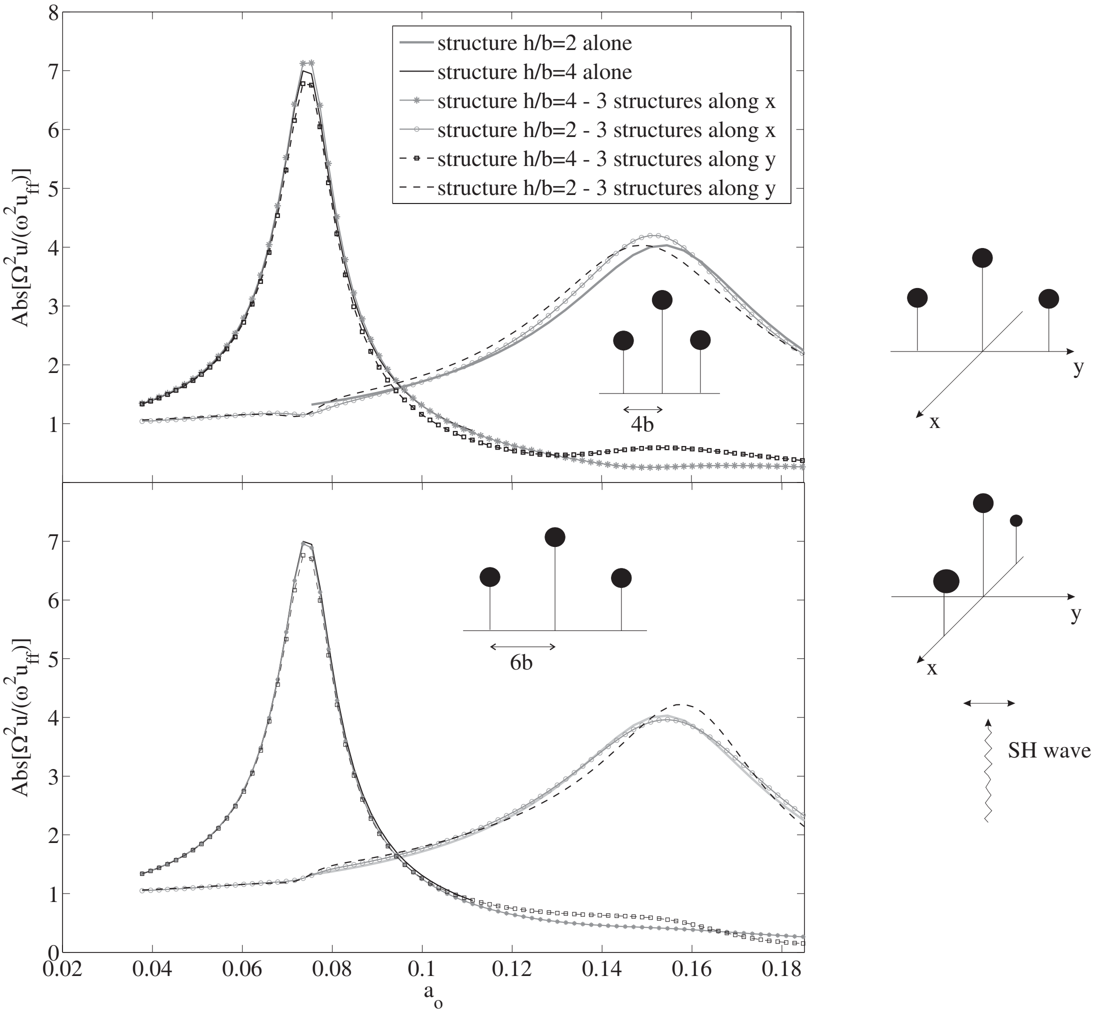

Fig. 2. Interaction between structures of non-similar fundamental frequencies in terms of their harmonic response spectra for different configurations.

fundamental frequencies highly modifies their dynamic response. In this case, the separation between adjacent structures is defined by the number of wave lengths between middle points of adjacent structures at the flexible-base structure fundamental frequency. Although problems with the same number of wave lengths between adjacent structures are not equivalent because the foundation is the same while the aspect ratio changes, it is shown that the same trend occurs in these cases. For instance, all plots on the left correspond to a distance of half a wave length for structures with different aspect ratios, and in all cases the response of the structures aligned according to the incident wave shaking direction is amplified while the response of structures aligned on the *x* axis decrease. When the distance corresponds to a quarter of wave length all responses decrease, but when it corresponds to three quarters, all responses increase. A different phenomenon that takes place when two or more similar structures interact is that a shifting in the flexible-base fundamental frequency of the system occurs, and it is different according to the distance, the structural characteristics and the direction of alignment.

The torsional motion of a symmetric structure alone (as that depicted in Fig. 1) to a vertically-incident SH wave acting along the *y* axis is null. However, the interaction between structures aligned along the *x* axis induces torsional motions. Fig. 4 presents the torsional motion of *two* structures of aspect ratios 2 and 4, and also, the torsional response of the lateral structure of the configuration of *three* different structures depicted in Fig. 2, with separations 4*b*. The torsional stiffness of the structures has been assumed to be very high, so that floor and cap present similar motions. It can be seen that the interaction exists and is even larger in the case of three buildings.

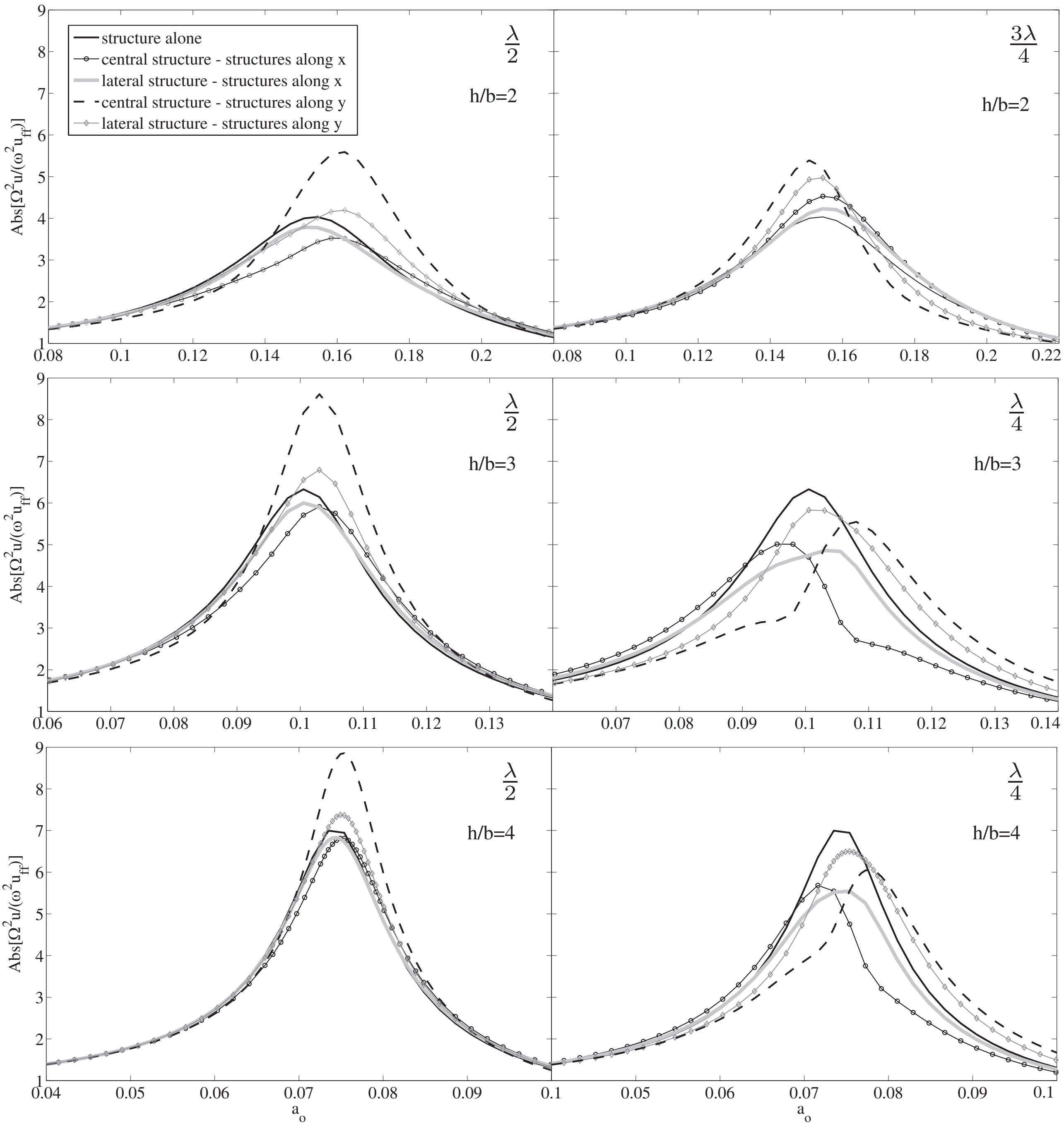

Fig. 3. Interaction between structures of identical fundamental frequencies in terms of their harmonic response spectra for different configurations.

Finally, the influence of the interaction between structures on the pile forces is illustrated in Fig. 5, where the shear forces on central and corner piles heads of the central structure foundation are shown for one $h/b = 4$ structure standing alone and *three* identical $h/b = 4$ structures separated $6b$. The shear forces are normalized by the static horizontal stiffness of a single pile. In this case, the importance of the interaction becomes apparent, as the amplitude of the shear forces increases up to 55% when the existence of other structures is taken into account.

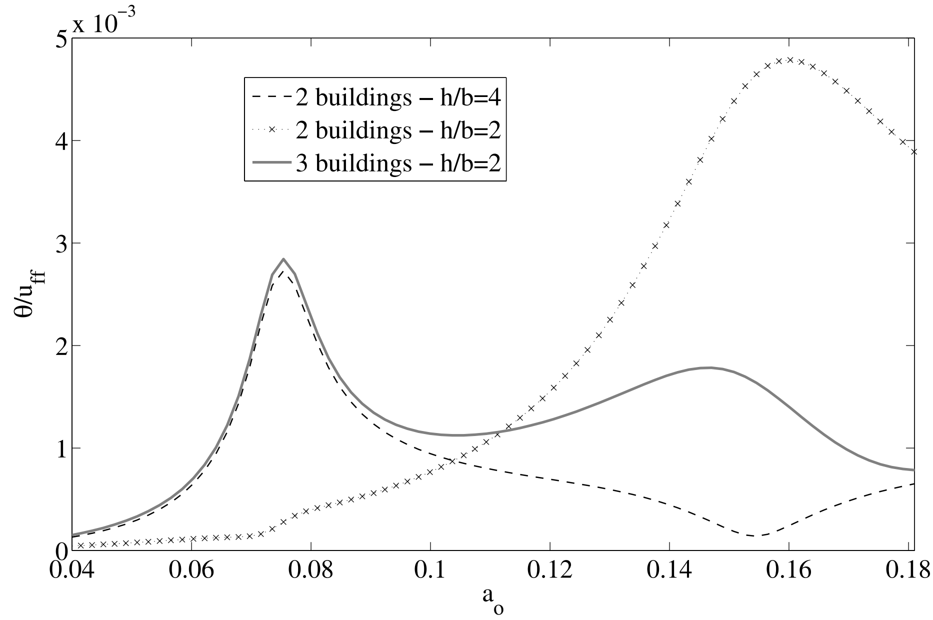

Fig. 4. Torsional motion due to interaction between adjacent structures.

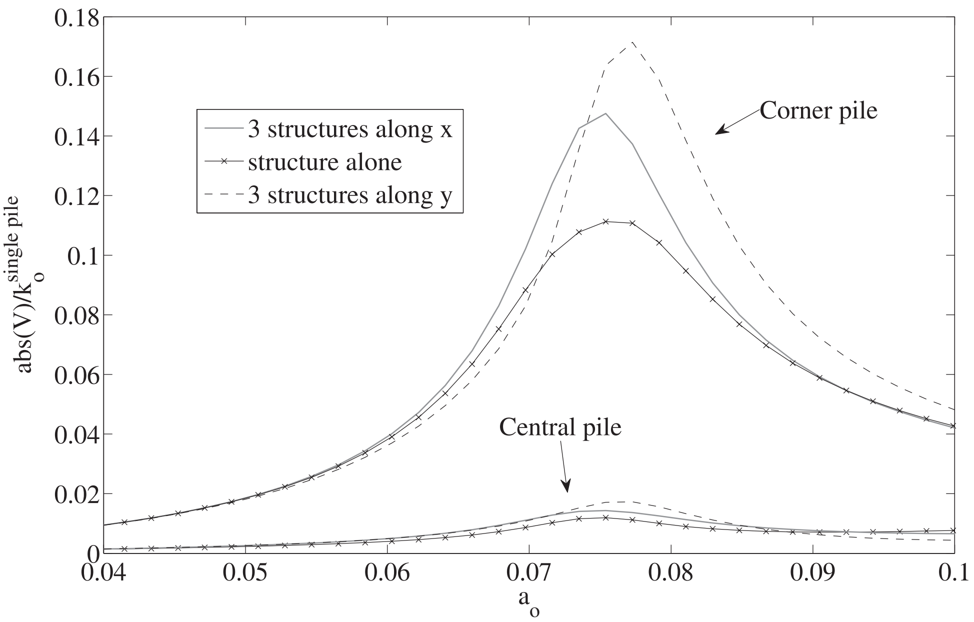

Fig. 5. Influence of the interaction between structures on the pile heads shear forces. Three identical $h/b = 4$ structures separated $6b$.

Conclusions

A BEM-FEM coupling model for the dynamic analysis of pile groups have been used to study the influence of neighbouring structures on the dynamic response of one-storey piled shear buildings subject to vertically-incident SH waves, through a direct approach. The structures have been considered to be founded on a viscoelastic half-space and several parameters such as aspect ratio and distance between adjacent structures have been taken into account.

The interaction between structures with non-similar fundamental periods have been found to be negligible, except for the fact that it induces torsional motions that may be significant on the dynamic behaviour of buildings. On the contrary, the dynamic response of the structures is modified when other structures with similar fundamental frequencies exist in its vicinity, both in amplitude and with respect to the system fundamental frequencies. However, the interaction is only significant at frequencies around resonance. Similar effects are observed in [5]. It is worth noting that the amplitude of the peak structural horizontal deformation can either increase or decrease in the presence of similar buildings, depending on the aspect ratios, the separation between adjacent buildings, the flexible-base fundamental frequency of the structures and the direction of alignment of the structures with respect to the seismic waves. Also, another variable of great importance from the engineering point of view, the maximum forces at the pile heads, has been shown to be highly influenced by the interaction between neighbouring structures.

These are just preliminary studies aimed at evaluating whether or not the dynamic response of a structure founded on soft to medium soils is modified by the presence of neighbouring structures. It has been found that the influence exists and can be of importance, so further studies will be made in order to investigate how parameters such as stratigraphy, foundation configuration, number and distribution of buildings, structural characteristics or type and angle of the incident waves modify the interaction phenomena. The response of the structures subject to recorded earthquake motions will also be investigating making use of the Fast Fourier Transform.

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References

[1] J. Bielak, *Dynamic behaviour of structures with embedded foundations*, Earthquake Eng Struct Dyn, **3**, 259-274 (1975)

[2] J. Avilés and L.E. Pérez-Rocha, *Effects of foundation embedment during building-soil interaction*, Earthquake Eng Struct Dyn, **27**, 1523-1540 (1998)

[3] J.P. Stewart, R.B. Seed and G.L. Fenves, *Seismic soil-structure interaction in buildings. I: Analytical methods*, J Geotech Eng, ASCE, **125** (1), 26-37 (1999)

[4] J.P. Stewart, R.B. Seed and G.L. Fenves, *Seismic soil-structure interaction in buildings. II: Empirical results*, J Geotech Eng, ASCE, **125** (1), 38-48 (1999)

[5] P.Y. Bard, P. Guéguen, J.L. Chazelas, M. Kham and J.F. Semblat, *Seismic hazard in urban environments: Can man modify the hazard?*, in Proc. of 3ed Congreso Nacional de Ingeniería Sísmica, Juan-Bautista Martínez-Guevara (Eds), CIMNE, Barcelona, 2007.

[6] L.A. Padrón, J.J. Aznárez and O. Maeso, *BEM-FEM coupling model for the dynamic analysis of piles and pile groups*, Engineering Analysis Boundary Elements, **31**, 473-484, (2007)

[7] L.A. Padrón, J.J. Aznárez and O. Maeso, *Dynamic analysis of piled foundation in stratified soils by a BEM-FEM model*, Soil Dynamics and Earthquake Engineering, *In Press.*

[8] J. Domínguez, *'Boundary elements in dynamics'*, CMP and Elsevier Applied Science, Southampton-New York, (1993).