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Structure-soil-structure interaction effects on the dynamic response of piled structures under obliquely incident seismic shear waves

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ABSTRACT

This work studies the structure-soil-structure interaction (SSSI) effects on the dynamic response of nearby piled structures under obliquely incident shear waves. For this purpose, a three-dimensional, frequency-domain, coupled boundary element – finite element (BEM–FEM) model is used to analyse the response of a configuration of three buildings aligned parallel to the horizontal component of the wave propagation direction. The SSSI effects are studied in terms of the maximum shear force at the base of the structures in both frequency- and time-domains. The results are presented in a set of graphs so that the magnitude of the interaction effects in configurations of buildings with similar vibration properties depending on the distance between them and the angle of incidence can be easily estimated. These results show a high influence of the wave type and angle of incidence on the interaction effects, not always corresponding the worst-case scenario with the commonly assumed hypothesis of vertical incidence. It is found that for configurations of non-slender structures, the SSSI effects can significantly amplify or reduce the single building maximum response depending on the separation between structures and excitation.

1. Introduction

When studying the seismic response of civil constructions, the structure is usually considered alone on the ground without any other near structures. However, this situation rarely happens in modern urban areas. When excited by a seismic input, the vibration of one structure propagates through the soil and reaches the nearby buildings, modifying their dynamic response. This effect is referred to as structure-soil-structure interaction (SSSI) and can either magnify or attenuate the structural response of a building.

To the best knowledge of the authors, some of the first works that proposed models for the quantification of SSSI effects are [1] (that studied the dynamic response of near nuclear reactors on rigid circular bases) and [2,3] (that studied the bidimensional interaction problem of buildings under antiplane shear waves). The results published in these papers proved that, in some cases, the interaction effects modify the structural response in a way that cannot be neglected. Following these pioneering works, several authors have tackled the SSSI problem through different methodologies, such as analytical solutions, numerical models and experimental tests. As a full literature review is out of the scope of this research, the authors want to refer the interested reader to the work of Lou et al. [4], where a complete survey of the SSSI studies can be found. Later publications that can also be consulted as interesting examples of SSSI studies are [5–7]. A related problem that has been addressed more recently [8–10] is that of the site-city interaction (SCI). These works showed that ground motion is affected by the presence of large groups of buildings and that the response of each structure varies significantly from one to another, in such a way that some of them may suffer high damages, while others will remain unaffected.

In most of those works, when studying the interaction phenomena, the seismic excitation is considered to propagate vertically through the terrain. However, Wong and Trifunac [3] studied the interaction between two buildings under SH waves with different angles of propagation. Their results showed different building responses depending on this incident angle. Up to the authors knowledge, no other works have studied the relation between the angle of incidence and the SSSI, being this an aspect of the interaction problem that demands further research.

On the other hand, the response of pile foundations under waves with a generic angle of propagation had been studied in terms of kinematic interaction factors in different works [e.g. 11–13]. One of the most extensive results were obtained by Kaynia and Novak [14] for different pile groups configurations under oblique volumetric waves and Rayleigh waves. These results demonstrate the importance of the angle of incidence in the dynamic response of this type of foundation.

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The objective of this work is to include the assumption of a generic angle of incidence in the SSSI study in order to analyse the influence of this parameter on the interaction effects. For this purpose, the dynamic response of a group of three piled structures subjected to planar oblique shear waves is obtained through a direct approach by using a previously developed BEM–FEM model [15,16]. Coupled BEM–FEM methodologies have been previously chosen by several authors to treat the SSSI problem. Wang and Schmid [17] and Lehmann and Antes [18] used different BEM–FEM models to study the interaction between near structures on embedded foundations. Wang and Schmid [17] used harmonic forces on the structures as the excitation, while Lehmann and Antes [18] placed the load on the ground surface. In their recent work, Clouteau et al. [19] compared the results obtained by their BEM–FEM model with an experimental test using mock-up structures built on unmade ground performed by the Nuclear Power Electric Corporation (NUPEC) in Japan. The numerical results were in good agreement with the experimental ones.

Along this study, the interaction effects will be quantified by comparing the maximum response of the group buildings with the maximum response of a single structure on the ground. The results, both in frequency- and time-domains, are presented in a set of graphs that allows to evaluate the importance of the SSSI depending on the configuration and excitation. Besides, these results can be understood as correcting factors that can be applied to simplified models in order to include the effects of near constructions and a non-vertical incidence.

2. Problem statement

2.1. Problem definition

A configuration of three one-storey shear structures founded on 3×3 fixed-head pile groups embedded on a viscoelastic half-space is studied. The three buildings are aligned with the horizontal component of the wave propagation direction in order to investigate the shielding effect produced by the presence of neighbour foundations in the wave course. The problem is sketched in Fig. 1. The geometric properties of pile groups are defined by: length L and diameter d of piles, center-to-center distance between adjacent piles s and foundation halfwidth b. The parameters that define the structures are: cap mass m_0 and moment of inertia I_0, fixed-base fundamental period T and structural damping ratio ζ, structure effective height h and mass m and distance between adjacent structures D. As the buildings are modelled as one-storey structures, the values of h, m and ζ can represent either the height, mass and damping of one-storey constructions or the ones equivalent to one particular mode of multi-mode structures.

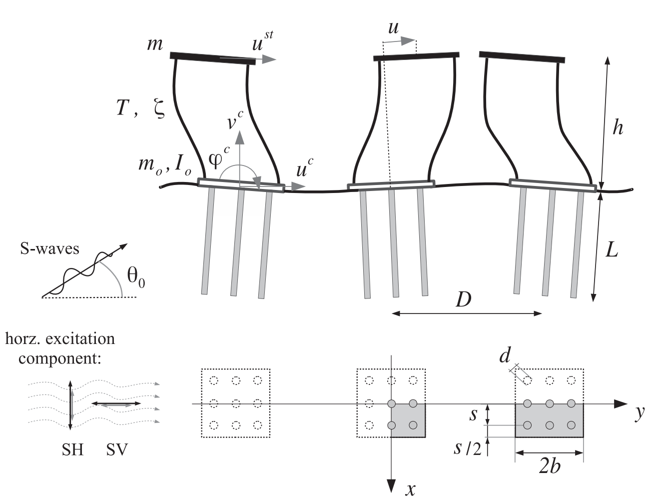

Fig. 1. Geometry, symmetry and degrees of freedom of the problem.

The dynamic response of each structure is represented by eight degrees of freedom corresponding to: horizontal translations of vibrating mass u^{st} and foundation u^c along the x and y axes, one vertical displacement v^c, two rocking motions φ^c around horizontal axes and one rotational motion ϕ^c around the vertical axis. As the buildings are modelled as shear structures, the vertical, rocking and rotational motions of cap and floor slab are assumed to be coincident.

The site is assumed to be excited by obliquely incident SH or SV waves producing horizontal displacements perpendicular or parallel to the alignment of the structures, and with a direction of incidence with respect to the horizontal defined by the angle θ_0 (see Fig. 1).

2.2. Problem parameters

The mechanical dimensionless properties of the pile–soil system are those presented in Table 1, which can represent reinforced concrete pile foundations in sandy soils. On the other hand, the constants defining the properties of the soil-structure system are listed in Table 2, where c_s is the soil shear wave velocity. These values were chosen in order to be representative for typical constructions and have been used in previous studies [20–23]. In order to see the dynamic behaviour of the selected soil-structure system, Fig. 2 shows the ratio between the flexible-base ($\tilde{T}$) and the fixed-base (T) fundamental periods depending on σ, for the properties defined above. These curves were obtained by following the methodology presented in [24]. Notice that as the value of $1/\sigma$ tends to zero (soft structures or stiff soils) the behaviour of the building tends to the fixed-base system one, so no soil-structure interaction (SSI) is observed. Despite typical buildings present a value of $1/\sigma$ lower than 0.1, the chosen value of 0.25 allows the SSI effects to be evident enough while being within the range of values that can be found among real cases ($1/\sigma < 0.4$) [25].

The distance between adjacent buildings will be expressed in terms of the soil wave length at the soil-structure fundamental frequency: $D \propto \lambda = c_s \tilde{T}$.

3. Methodology

The seismic response of the system is obtained through a previously developed three-dimensional frequency-domain BEM–FEM model

Table 1
Soil and piles properties.

Piles aspect ratio	L/d	15
Piles separation ratio	s/d	5
Pile–soil modulus ratio	E_p/E_s	100
Soil–pile density ratio	ρ_s/ρ_p	0.7
Soil Poisson ratio	ν_s	0.4
Soil hysteretic damping ratio	β	0.05
Complex soil shear modulus	$\mu =$ Re $[\mu]$ $(1+2\,\mathrm{i}\,\beta)$	

Table 2
Soil-structure system properties.

Structural aspect ratios	h/b	2, 3, 5
Structure-soil stiffness ratio [20]	$1/\sigma = h/(Tc_s)$	0.25
Structure-soil mass ratio	$\delta = m/(4\rho_s b^2 h)$	0.15
Foundation-structure mass ratio	m_0/m	0.25
Foundation moment of inertia	$I_0/(mh^2)$	0.05
Structure hysteretic damping ratio	ζ	0.05
Complex structural stiffness	$k = Re[k]\,(1+2i\zeta)$	