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Effects of soil–structure interaction on the dynamic properties and seismic response of piled structures

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ABSTRACT

This paper presents a simple and stable procedure for the estimation of periods and dampings of piled shear buildings taking soil–structure interaction into account. A substructuring methodology that includes the three-dimensional character of the foundations is used. The structure is analyzed as founded on an elastic homogeneous half-space and excited by vertically incident S waves. The strategies proposed in the literature to estimate the period and damping are revised, and a modified strategy is proposed including crossed impedances and all damping terms. Ready-to-use graphs are presented for the estimation of flexible-base period and damping in terms of their fixed-base values and the system configuration. Maximum shear forces together with base displacement and rocking peak response are also provided. It is shown that cross-coupled impedances and kinematic interaction factors need to be taken into account to obtain accurate results for piled buildings.

1. Introduction

When analysing the seismic behaviour of structures, kinematic and inertial effects associated to soil–structure interaction (SSI) affect the dynamic characteristics of the interacting system and influence the ground motion around the foundation. Thus, it is important to assess the variations of the system period associated with the soil stiffness, as well as the variations of the modal damping associated with the material damping in the soil and especially with the radiation effects.

The effects of SSI on the dynamic characteristics of soil–structure systems have been widely studied both for shallow foundations [1–6] and for embedded foundations using both 3D models [7–10] and 2D models [11,12]. The papers by Jenning and Bielak [4], Veletsos and Meek [2], Luco [5], Wolf [6] or Bielak [7] all introduce the analogy of a fixed-base replacement SDOF oscillator whose period and damping can represent the dynamic behaviour of the structure–foundation system. In all these pioneering works, some simplifying assumptions were used in order to obtain results or expressions for the effective system period and damping: the influence of the coupled terms of the soil-impedance matrix was neglected and, for embedded foundations, the kinematic effects of the incident wave were not considered, using as base excitation a horizontal harmonic motion with constant amplitude. In contrast, the effects of the foundation embedment considering both kinematic and inertial interaction were taken into account by Avilés and Pérez-Rocha [9] (for 3D rectangular foundations), by Avilés and Suárez [13] (for axisymmetrical embedded foundations in a layer), and by Todorovska [11] and Todorovska and Trifunac [12,14] who presented a 2D model with analytical solutions for impedances and kinematic effects for very long buildings founded on rigid cylindrical foundations. Also, Todorovska and Trifunac [12,14] and Avilés et al. [10] for problems with square embedded foundations, studied the effects of the type of waves and their angle of incidence on the system frequency and damping.

Regarding pile-supported buildings, and to the extent of the authors' knowledge, there are few studies in the scientific literature examining the effects of SSI on their dynamic characteristics [15–18]. Rainer [15] used a substructuring methodology to analyse the modal damping of a superstructure supported on piles. Kaynia and Mahzooni [16] used a three-dimensional Green's functions-based formulation, for the pile foundation, and a single-degree-of-freedom (SDOF) model for the structure, in order to calculate the seismic shear forces in the piles during the seismic kinematic and inertial interaction phases for different pile foundations. On the other hand, Aguilar and Avilés [17] analysed piled foundations by extending the Avilés and Pérez-Rocha's [9] procedure for embedded foundations and thus they studied the SSI effects on the system period and damping for a specific configuration of 8×8

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piles. Moreover, Maravas et al. [18] presented a simple methodology in order to study SSI effects on single-pile supported one-storey shear structures by obtaining its period and damping. However, there are no parametric studies of this nature for piled foundations consisting of a variable number of piles, with different embedments and spacings between them.

Following the reference works for shallow and embedded foundations systems, the aim of this work is to evaluate the influence of SSI on the period and damping of shear structures founded on square pile groups embedded in homogeneous viscoelastic half-spaces subjected to vertically incident S waves. The analysis is performed by a substructuring model in the frequency domain that takes into account both kinematic and inertial interaction effects. In this study, the harmonic response of the soil–structure system is obtained by making use of impedance functions and kinematic interaction factors computed by a BEM–FEM coupling model developed by Padrón et al [19].

The effective period and damping of the interacting system ($\tilde{T}$ and $\tilde{\xi}$) [2,7–9,14] represent the dynamic parameters of an equivalent viscously damped SDOF system excited by the free-field ground motion. This replacement oscillator will reproduce, as accurately as possible, the coupled system response within the range where the peak response occurs. A comparative review of the different strategies used in the literature for establishing this equivalence and calculating the parameters of this single-degree-of-freedom system is presented, identifying those that best suit to the problem under study and proposing a modification. Thus, a simplified and stable procedure, which takes into account all the elements of the matrix of impedances, is developed herein. The accuracy of this simplified procedure is assessed through comparisons with the solution obtained from the iterative resolution of a complex-valued system of equations which represents the equation of motion of the interacting system. Results in terms of period $\tilde{T}/T$ and damping $\tilde{\xi}$ for different pile configurations are provided in ready-to-use graphs that can be used to build modified response spectra that include SSI effects.

All equations are expressed in terms of the main dimensionless parameters of the problem which considerably facilitates the analysis of their influence on the system dynamic response. The influence of the more important parameters involved (wave parameter, slenderness ratio, spacing between adjacent piles, embedment ratio and number of piles) is analysed over practical ranges of interest. Moreover, the influence of the consideration of the cross-coupled impedance and the kinematic interaction factors for the pile-groups configurations is also studied.

2. Problem definition

The dynamic response of pile-supported linear shear structures is investigated in this work making use of a single-degree-of-freedom system in its fixed-base condition, as the one depicted in Fig. 1, that may represent either one-storey structures or one mode of vibration of multi-storey buildings. The superstructure can be defined by its fixed-base period T, its mass m, the structural stiffness k, the height h of the resultant of the inertia forces for the mode, the moment of inertia of the vibrating mass I, and the viscous damping ratio ξ. The structure is considered to be founded on a square pile group embedded in a homogeneous, viscoelastic and isotropic half-space, as depicted in Fig. 1. It is assumed that the pile heads are constrained by a rigid pile cap, considered as a rigid square plate of negligible thickness, which is not in contact with the half-space. The pile group is defined by length L and sectional diameter d of piles, centre-to-centre spacing between adjacent piles s, cap mass m_o, and cap moment of inertia about the centre of gravity of the cap I_o. The foundation halfwidth is denoted by b. The columns of the structure

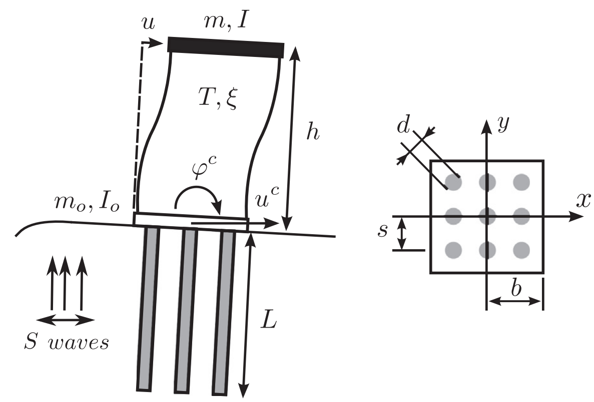

Fig. 1. Problem definition. Single shear structure supported on a piled foundation embedded in a homogeneous half-space under vertically-incident S waves.

are assumed to be massless and axially inextensible. Both the foundation mass and the mass of the structure are presumed to be uniformly distributed over square areas. This model of the foundation–structure system is an enhancement of that which appears to have been first used by Parmelee [20] in 1967 for shallow foundations and, according to Veletsos and Meek [2], has formed the basis of most subsequent investigations.

If SSI is taken into account, the system behaviour can be approximated by that of a three-degree-of-freedom system, defined by the foundation horizontal displacement u^c and rocking φ^c, together with the structural horizontal deflection u (Note that rocking of pile cap and structure are identical). The system is subjected to vertically incident plane S waves. Because of the characteristics of the structural model and the wave excitation, the vertical and torsional motions are neglected in this study.

3. Substructure model

This problem can be studied using a substructure approach, in which the system is subdivided into *building-cap* superstructure and *soil-foundation* stiffness and damping, represented by means of springs and dashpots, as shown in Fig. 2. According to Kausel and Roësset [21], the solution can be broken into three steps. In the present case, the first step (kinematic interaction) consists in the determination of the motion of the massless pile cap when subjected to the same input motion as the total solution. Even for vertically incident harmonic plane S waves (in which the free-field displacement at the ground surface is exclusively horizontal), this frequency dependent kinematic interaction factors are represented by horizontal (u_g) and rocking (φ_g) motions at the pile cap. The next step is to determine the impedances, which are complex-valued frequency-dependent functions (k_{xx}, c_{xx}), $(k_{\theta\theta}, c_{\theta\theta})$ and $(k_{x\theta}, c_{x\theta})$ that represent the stiffness and damping of the soil in the horizontal, rocking and cross-coupled horizontal-rocking vibration modes, respectively. The mathematical representation of impedance functions is $K_{ij} = k_{ij} + \mathrm{i}a_o c_{ij}$, where $a_o = \omega b / c_s$; being ω the excitation circular frequency, $c_s = \sqrt{\mu_s/\rho_s}$ the speed of propagation of shear waves in the halfspace, and μ_s and ρ_s the soil shear modulus of elasticity and mass density, respectively. Finally, the last step consists in the computation of the response at each frequency of the structure supported on springs and subjected to the motion computed in the first step (see Fig. 2a).

3.1. Equations of motion

The equations of motion of the system shown in Fig. 2(a), assuming small displacements, can be written in terms of relative