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Dynamic analysis of piled foundations in stratified soils by a BEM–FEM model

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Abstract

In this paper, a 3D BEM–FEM coupling model is used to study the dynamic behavior of piled foundations in elastic layered soils in presence of a rigid bedrock. Piles are modelled by FEM as beams according to the Bernoulli hypothesis, and every layer of the soil is modelled by BEM as a continuum, semi-infinite, isotropic, homogeneous, linear, viscoelastic medium. First, the main points of the model are set out. Then, several results of vertical, horizontal and rocking impedances for single piles and 2×2 pile groups embedded in a stratum resting on a rigid bedrock, are presented. The influence on the dynamic response of stratum depth, soil stiffness and piled foundation configuration is discussed. Finally, the influence of the stratigraphy on the seismic response of a 3×3 pile group is analyzed, together with the pile-to-pile kinematic interaction and the wave-scattering phenomena.

Keywords: Pile groups; Pile–soil interaction; Dynamic impedances; Seismic response; BEM–FEM coupling

1. Introduction

The steady-state dynamic response of piled foundations in elastic soils has been the subject of much research, in both the kinematic and the forced vibration analyses (see e.g. [1]). For the study of piles and pile groups embedded in a homogeneous half-space, several frequency domain boundary integral formulations in conjunction with the monodimensional finite element method (FEM) have been used by different authors [2–5]. Linear analyses for non-homogeneous media or layered soils have also been carried out using the same kind of approach [6–9]. Subsequently, more versatile and rigorous linear numerical models have been developed using the boundary element method (BEM) for both soil and piles [10–13], but with the disadvantage of a high computational cost.

Although a great deal of this research has been focused on the forced vibration problem, much of it has also dealt with the kinematic response of piled foundations. For instance, parametric studies of the seismic response of single piles and pile groups to Rayleigh waves and to vertically and obliquely incident body waves have been reported in [14–17].

On the other hand, due to the fact that piles are commonly used when avoiding shallow soil of low bearing capacity and transferring load to deeper soil or rock of high bearing capacity is needed, a particular case of interest in the dynamic analysis of piles is that of piled foundations embedded in a viscoelastic stratum resting on a rigid bedrock, for both floating and hinged piles. However, not many papers have been reported focusing on this topic [18,19], though some have dealt with it while studying the pile–soil-structure interaction problem [20–23].

For this reason, the aim of this paper is to present a method for the dynamic analysis of piles and pile groups and, making use of it, contribute to the topic discussed above by investigating, through parametric studies: (a) the influence of the presence of a rigid bedrock on the dynamic impedances of piled foundations, and (b) the influence of the stratigraphy on the seismic response of hinged pile groups. To this end, a BEM–FEM coupling model previously

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presented by the authors [24] is used to compute time-harmonic dynamic impedances and the seismic response of piled foundations embedded in viscoelastic zoned-homogeneous layered soils. The model has been validated for both the kinematic and the stiffness problems with several results taken from the literature (e.g. [2,18–20]), though these comparisons are not presented here for the sake of brevity.

In this approach, and in the line of a previous static model developed in [25–27], the pile–soil interaction takes place, from the integral equation point of view, through internal forces, as it is assumed that the soil continuity is not altered by the presence of the piles. These are modeled by FEM as beams according to the Bernoulli hypothesis, and every stratum of the soil is modeled by BEM as a continuum, semi-infinite, isotropic, homogeneous, linear, viscoelastic medium. The model not only allows the dynamic analysis of piled foundations embedded in a half-space or in a stratum resting on a rigid bedrock, but also in multilayered soils of generic stratigraphy and topography, including deposits and inclusions.

Firstly, the main points of the BEM–FEM coupling model formulation are set out. Secondly, several results of vertical, horizontal and rocking time-harmonic dynamic impedances of single piles and 2×2 pile groups embedded in a stratum resting on a rigid bedrock, are presented. Different depths of the stratum and three foundation configurations are studied, and the effects associated to these parameters are discussed. Finally, the influence of the stratigraphy on the seismic response of a 3×3 pile group is analyzed. To this end, displacement transfer functions for vertically incident plane time-harmonic shear waves and response spectra for a particular configuration, under two different strong ground motions, are presented for several soil profiles. Pile-to-pile kinematic interaction and wave-scattering phenomena, are also investigated.

Regarding the impedances study, it is shown that the effect of the presence of the rigid bedrock is vital for the horizontal impedance of single piles and pile groups, and also for the rocking behavior of single piles, while it is almost negligible for the rocking response of pile groups. Regarding the vertical impedances of floating piled foundations, the effect of the bedrock is not important except for frequencies below 1.5 times the fundamental natural frequency of the stratum.

As for the performed seismic analysis, it can be seen that the presence of a soft layer at the top of a stratum yields to rapidly decreasing transfer functions and, consequently, to a weakened seismic response at the pile cap. However, taking into account additional layers with shear wave velocity increasing with depth is of minor importance.

2. Pile–soil interaction model

The behavior of a pile submitted to harmonically varying loads, considering zero internal damping, can be described by the equation

$$\bar{\mathbf{K}}\,\mathbf{u}^{\mathrm{p}} = \mathbf{F}^{\mathrm{ext}} + \mathbf{Q}\mathbf{q}^{\mathrm{p}}, \tag{1}$$

where $\bar{\mathbf{K}} = \mathbf{K} - \omega^2\mathbf{M}$, being $\mathbf{K}$ and $\mathbf{M}$ the stiffness and mass matrices of the pile, ω is the circular frequency of excitation, and $\mathbf{u}^{\mathrm{p}}$ the vector of nodal translation and rotation amplitudes along the pile. $\mathbf{F}^{\mathrm{ext}}$ includes the forces at the top $\mathbf{F}_{\mathrm{top}}$ and the axial force at the tip of the pile $\mathbf{F}_{\mathrm{p}}$, $\mathbf{q}^{\mathrm{p}}$ is the vector of tractions along the pile–soil interface, whereas $\mathbf{Q}$ is the matrix that transforms these nodal traction components to equivalent nodal forces. By means of Eq. (1), piles are modelled as vertical Bernoulli beams by three-node FEM elements on which there are defined 13 degrees of freedom: three lateral displacements on each node, and two rotations on each one of the extreme nodes.

On the other hand, each stratum of the soil is modelled by BEM as a linear, homogeneous, isotropic, viscoelastic, unbounded region. The boundary integral equation for a time-harmonic elastodynamic state defined in a domain Ω_m with boundary Γ^m can be written in a condensed and general form as

$$\mathbf{c}^k\mathbf{u}^k + \int_{\Gamma^m} \mathbf{p}^*\mathbf{u}\,\mathrm{d}\Gamma = \int_{\Gamma^m} \mathbf{u}^*\mathbf{p}\,\mathrm{d}\Gamma + \int_{\Omega_m} \mathbf{u}^*\mathbf{X}\,\mathrm{d}\Omega, \tag{2}$$

where $\mathbf{c}^k$ is the local free term matrix at collocation point 'k', $\mathbf{X}$ are the body forces in the domain Ω_m, $\mathbf{u}$ and $\mathbf{p}$ are the displacement and traction vectors, and $\mathbf{u}^*$ and $\mathbf{p}^*$ are the elastodynamic fundamental solution tensors for a time-harmonic concentrated load at point 'k'. A hysteretic damping model is used for the soil through a complex valued shear modulus μ of the type $\mu = \mathrm{Re}[\mu](1 + 2\mathrm{i}\xi)$, being ξ the damping coefficient. Details about BEM formulation can be found in [28].

Generally, body forces $\mathbf{X}$ are considered to be zero in most of elastodynamic problems. Nevertheless, in this approach, from the integral equation point of view, the pile–soil interaction takes place through internal punctual forces placed at the geometric piles tip and through load-lines placed along the piles axis, as it is assumed that the soil continuity is not altered by the presence of the piles. The load-lines within the soil, the tractions along the pile–soil interface acting over the pile and within the soil ($\mathbf{q}^{\mathrm{p}_j} = -\mathbf{q}^{\mathrm{s}_j}$), and the internal punctual forces F_{p_j} at the tip of the piles, are represented in Fig. 1, where a sketch of the model is shown.

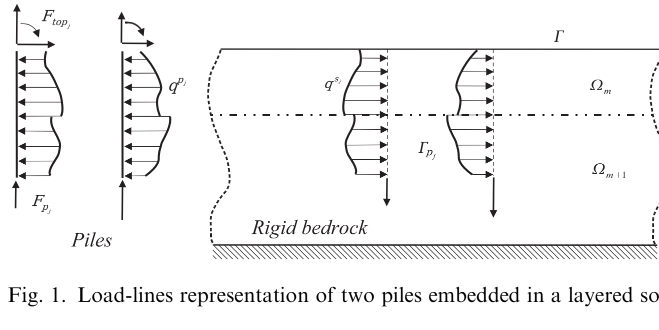

Fig. 1. Load-lines representation of two piles embedded in a layered soil.