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Efficient numerical model for the computation of impedance functions of inclined pile groups in layered soils

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ABSTRACT

This paper introduces a numerical model to obtain the time-harmonic dynamic response of pile foundations in non-homogeneous soils. The model is based on the integral formulation of the elastic problem and the use of Green's functions for the layered halfspace, and considers the soil as a group of zoned homogeneous, linear, isotropic, viscoelastic layers. The piles, on the other hand, are treated by finite elements as Timoshenko beams. Both formulations are coupled through the required compatibility and equilibrium equations along each pile. After being validated against previous results from the literature, the model is used to study the effects of soil non-homogeneity on the impedance functions of inclined piles and pile groups by considering different soil profiles whose properties vary with depth following a generalized power law. The impedance functions for three representative non-homogeneous soils are presented and compared with the ones of related homogeneous soils. Significant differences appear between the two situations for all studied rake angles. The magnitude of these differences strongly depends on the frequency range considered, specially for the case of pile groups, which shows the necessity of analyzing the problem using soil profiles as close as possible to the actual depth-varying ones.

1. Introduction

In situations where loads with great horizontal components are present inclined piles are used in combination with vertical piles to increase the foundation lateral stiffness. For the last decades, the use of inclined piles in seismic events has been strongly discouraged by several codes [1,2] due to the bad performance observed in various earthquakes during the 90s. Nevertheless, in the last years the use of inclined piles has increased again and some studies have revealed that they might have a beneficial effect not only for the foundation, but for the superstructure too [3–6]. However, further study is needed in order to achieve a better understanding of the dynamic behavior of raked pile foundations.

Despite the fact that seismic response of inclined piles has been the object of analysis for different studies [e.g. 5–10], the impedance problem of this type of pile foundation has received little attention. Impedance functions for specific configurations of inclined pile groups were studied by Mamoon et al. [11] for a 3×3 pile group with a rake angle of $\theta = 15^\circ$. Padrón et al. presented a complete set of impedance functions for configurations of single piles and pile groups embedded in an homogeneous halfspace [12] and in a soil layer resting on a bedrock [13]. A strong dependence on the configuration and rake angle was found for the group impedances, specially in the rocking and cross horizontal-rocking ones. Model tests on a single battered pile [14] and a 2×2 group [15] in dry cohesionless soil were carried out by Goit and Saitoh. In the first study, a comparison with a FEM numerical model was made, while in the latter the effects of soil non-linearity were analyzed. In their recent work, Dezi et al. [16] introduced a numerical model for the analysis of pile foundations in layered soil deposits and presented impedance functions for 2×2 inclined pile groups embedded in an homogeneous soil deposit and in a two-layered soil deposit over a rigid bedrock.

In the aforementioned papers only homogeneous halfspaces or up to two-layered soil deposits were considered. However, real soils can present properties that vary with depth and the assumption of soil homogeneity can lead to misleading predictions of the

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foundation behavior in the actual profile. Up to the authors' knowledge, only Giannakou et al. [17] have presented dynamic impedances for a single inclined pile in a soil profile whose properties vary continuously with depth.

For vertical pile foundations in non-homogeneous soils, the impedance problem has been studied by several authors with different methodologies. Velez et al. [18] employed a FEM formulation to obtain the lateral impedance of a single end-bearing pile in a non-homogeneous soil deposit overlaying a rigid bedrock. The results for the non-homogeneous media were compared against the ones corresponding to an 'statically equivalent' homogeneous deposit, showing that the static equivalence does not guarantee identical pile response under dynamic loads. Kaynia and Kausel [19], followed by Miura et al. [20], used a three-dimensional formulation based on Green's functions of cylindrical loads in layered semi-infinite media and presented a wide set of results for single piles and pile groups embedded in different soil profiles. Their results revealed that the horizontal impedance is more affected by near-surface soil properties than the vertical one, and that the interaction effects between the group piles are more pronounced in the non-homogeneous medium. Mylonakis and Gazetas [21,22] presented a Winkler model to solve this problem. For pile groups, the pile-soil-pile effects were considered through interaction factors [23,24] which relate the response of a 'receiver' pile to the oscillation of a near ('source') pile. The behavior of the non-homogeneous media was represented by a transfer-matrix formulation [25,26]. The same methodology has been used by other authors to handle the impedance problem in non-homogeneous media [27–29]. In their recent work, Rovithis et al. [29] studied the lateral impedance of a single pile in a soil profile with properties varying according to a power law. Their results showed that lateral damping is overestimated when using the homogeneous assumption, leading to an un-conservative evaluation of the lateral pile deflections at high frequencies. This conclusion agrees with the results obtained by Giannakou et al. [17] for a lineal-varying non-homogeneous soil with a FEM model.

2. Efficient integral model for the dynamic analysis of inclined piles foundations

This paper describes an efficient model for the computation of impedance functions of inclined piles and pile groups in layered soils. The presented procedure is inspired by a previous formulation developed by Padrón et al. [30,31], now using the Green's functions developed by Pak and Guzina [32] for the layered halfspace instead of the fundamental solution for the homogeneous entire space [33]. These Green's functions verify the free-surface, layer interfaces and radiation conditions. Thus, the proposed model avoids the need to discretize any boundary, which significantly reduces both the computational requirements and the numerical errors derived from the surface meshing. The model can be applied to study soils whose properties vary continuously with depth by modeling the continuous non-homogeneity through multiple zoned-homogeneous horizontal layers.

2.1. Model hypotheses

Inclined piles are modeled by finite elements as Timoshenko beams with hysteretic damping and neglecting their torsional resistance, while soil is considered as a semi-infinite region with different homogeneous, linear, isotropic, viscoelastic horizontal layers. The soil complex shear modulus μ_s is defined by the hysteretic damping coefficient β, as $\mu_s = Re[\mu_s](1+2\beta \mathrm{i})$, being i the imaginary unit. Welded boundary contact conditions at the pile-soil interfaces are assumed.

The proposed model assumes that soil continuity is not altered by the presence of piles, considering the tractions in the pile-soil interface as loads applied within the halfspace in the integral representation of the soil. This idea has already been used by previous static [34–36] and dynamic [30,31] models.

2.2. Piles equations

The differential equation that determines the pile behavior under dynamic loads has the following expression:

$$\mathbf{M}\ddot{\mathbf{u}}(t) + \mathbf{C}\dot{\mathbf{u}}(t) + \mathbf{K}\mathbf{u}(t) = \mathbf{f}(t) \tag{1}$$

where $\mathbf{M}$, $\mathbf{C}$ and $\mathbf{K}$ are the mass, damping and stiffness matrices respectively, $\mathbf{u}(t)$ the vector of nodal displacements and $\mathbf{f}(t)$ the vector of external nodal loads. Considering harmonic loads ($\mathbf{u}(t) = \mathbf{u}e^{\mathrm{i}\omega t}$ and $\mathbf{f}(t) = \mathbf{F}e^{\mathrm{i}\omega t}$) and hysteretic damping defined by the pile damping coefficient ζ:

$$\mathbf{K}^* = \mathbf{K}(1+2\zeta \mathrm{i}) \tag{2}$$

Eq. (1) can be expressed as:

$$\overline{\mathbf{K}}\mathbf{u} = \mathbf{F} \quad \text{with} \quad \overline{\mathbf{K}} = \mathbf{K}^* - \omega^2\mathbf{M} \tag{3}$$

where $\mathbf{u}$ and $\mathbf{F}$ are the vectors of nodal displacements and loads amplitudes and ω the excitation frequency.

Piles are discretized into 10 degrees-of-freedom 2-noded elements (Fig. 1(a)). Cubic shape functions for lateral displacements and quadratic shape functions for rotations, all satisfying the homogeneous static equation of the Timoshenko beam, are used [37]. For longitudinal displacements, linear shape functions are used. The stiffness and mass (translational plus rotational) matrix coefficients are obtained through the Hamilton's principle and are detailed together with the shape functions in [37]. As the piles are assumed not to affect the soil continuity, a reduced density must be considered for the piles (by subtracting the soil density: $\bar{\rho}_p = \rho_p - \rho_s$) in order not to overestimate the total system mass. A similar consideration was assumed in [24,30].

The external forces acting over the pile can be separated into:

$$\mathbf{F} = \mathbf{F}^{top} + \mathbf{F}^{eq} \tag{4}$$

where $\mathbf{F}^{top}$ are the external forces at piles head and $\mathbf{F}^{eq}$ are the equivalent nodal forces due to the soil-pile interaction which are obtained as $\mathbf{F}^{eq} = \mathbf{Q}\ \mathbf{q}^p$, where $\mathbf{Q}$ is the matrix that transforms nodal values of distributed tractions along the pile ($\mathbf{q}^p$) into equivalent nodal forces.

The coefficients of the matrix $\mathbf{Q}$ are obtained by using the principle of virtual displacements and the traction and

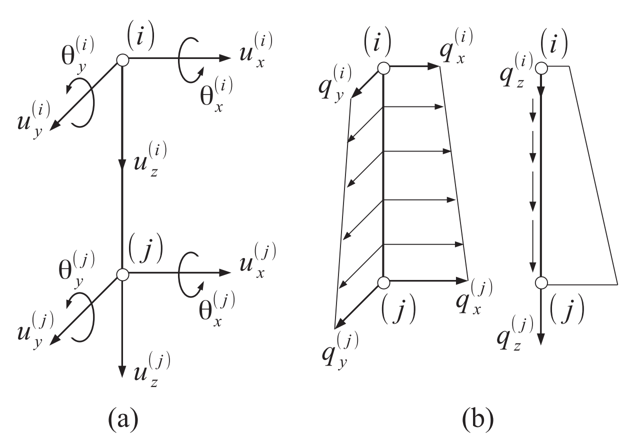

Fig. 1. FEM pile elements. (a) Definition of degrees of freedom. (b) Linear approximation of tractions along the elements.