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TIME-HARMONIC RESPONSE OF LARGE-SCALE PILE GROUPS UNDER SEISMIC EXCITATION

Ana C. A. Vasconcelos
Josué Labaki
a209494@dac.unicamp.br
labaki@fem.unicamp.br
Universidade Estadual de Campinas
Rua Mendeleyev 200, 13083-860, Campinas, São Paulo, Brasil

Abstract. Models of the dynamic response of embedded pile groups are fundamental for our understanding of their interaction with the surface structure. This understanding is especially important when the surface structure has particularly strict vibration requirements, such as particle accelerators, nuclear powerplants, and concert halls. This work presents an implementation of the impedance matrix method for the vibration of pile groups. Especial attention is given to the case of large-scale pile groups, due to our goal of modeling and understanding the response of the foundations of a large synchrotron-light source. The impedance matrix method comprises deriving the flexibility matrix of each layer of soil and of discretized segments along the body of the pile, and obtaining the impedance matrix of the pile-soil system by establishing direct kinematic compatibility and equilibrium conditions at their interface. The soil part is modeled as a isotropic, three dimensional half-space, the solution of which is obtained by the superposition of classical Green's functions for such medium. The piles are modeled as one-dimensional finite beam elements. Vertically-propagating time-harmonic shear seismic waves are incorporated as excitation sources. The paper presents strategies to deal with the high computational cost of such large-scale models involving the integration of Green's functions for soil media. The response of different constitutive and geometric parameters of the embedded pile group and layered soils are highlighted in the response of the system to such excitations.

Keywords: Large pile groups, Parallel computing, Dynamic soil-structure interaction

1 Introduction

The interest in controlling the dynamic response of surface structures submitted to seismic excitation has been a task of constant investigation in earthquake geotechnical engineering. An alternative to such control is the addition of a pile group in order to dissipate a part of the energy from a seismic wave.

A considerable quantity of numerical methods has been developed for predicting the pile-soil behavior in seismic conditions. These methods can be divided into two categories: Winkler-type approach and continuum-based approach. The first category consists of modelling the pile-soil interaction through continuously distributed springs and dashpots. Nogami [1], Kavvads and Gazetas [2], Mylonakis et al. [3] and Nikolaou et al. [4] used the Winkler model to determine the kinematic response of piles. Despite of its relatively simplicity, this model has some limitations in respect to the evaluation of the spring constant, which depends on the soil and the pile properties, and the treatment of the soil continuity, since the soil is represented by a series of independent springs and hence the displacements of springs are independent from each other. The second category treats the pile-soil interaction in terms of continuum mechanics. Since the analytical investigation of this interaction is very difficult to solve, approximate solutions based on finite element method (Wolf and Von Arx [5], Waas and Hartmann [6] and Maheshwari et al. [7]) and boundary element method (Banerjee [8], Banerjee [9] and Kaynia and Kausel [10]) were developed. The latter work solution is a consolidated formulation based on the use of Green's functions for an isotropic, three-dimensional half-space to obtain the displacement field due to cylindrical and circular loads. This displacement field yields the soil dynamic flexibility matrix which is combined with the pile dynamic flexibility matrix through the direct kinematic compatibility and equilibrium conditions at their interface to obtain the impedance matrix of the pile-soil system.

This work presents an implementation of the impedance matrix method proposed by Kaynia and Kausel [10] for the vibration of large pile groups. In order to deal with the high computational cost of the integration of Green's functions for soil media, strategies are incorporated at the present implementation. Some of them are straightforward computational schemes to assign expensive parts of the code to parallel CPU and graphics-hardware devices. Other strategies have been shown by the authors in other works, such as using less computationally-expensive, relaxed bonding conditions between the piles whenever possible. In the present study, it is assumed that the seismic excitation is due to vertically propagating shear waves. The response of the pile group-soil system submitted to such excitation is also investigated for different constitutive and geometric parameters.

2 Formulation

The present formulation is based on the impedance stiffness method proposed by Kaynia and Kausel [10]. This method considers the soil as a layered, isotropic, three-dimensional viscoelastic half-space. Its elasticity modulus, mass density, Poison ratio, shear modulus and material damping are denoted by E_s, ρ_s, ν_s, μ_s and β_s. The piles are modeled as one-dimensional beam elements. The diameter, length, Poison ratio, material damping, elasticity modulus and mass density of the pile are denoted by d_p, l_p, ν_p, β_p, E_p, ρ_p. The term s represents the center-to-center distance between adjacent piles. In order to represent the pile-soil interface tractions, cylindrical horizontal and vertical loads are included, as body forces, throughout the depth of each layer, whereas circular horizontal and vertical loads correspond to boundary conditions. Figure 1 shows the pile group model approached in this work.

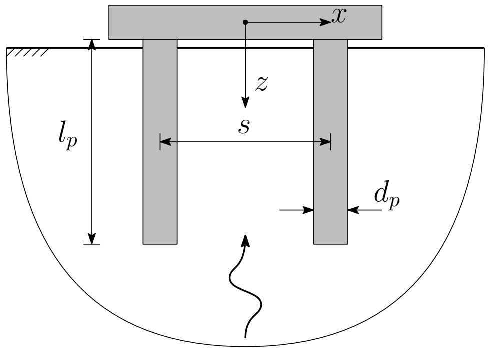

Figure 1. Model of a pile group submitted to a vertically-propagating shear wave

The impedance matrix of the pile groups relates the components of forces at each end of the piles to their corresponding displacements, that is,

$$\mathbf{P_e} = [\mathbf{K_p} + \mathbf{\Psi}^T(\mathbf{F_s} + \mathbf{F_p})^{-1}\mathbf{\Psi}]\mathbf{U_e} = \mathbf{K_e}\mathbf{U_e}, \tag{1}$$

where $\mathbf{K_p}$ is the dynamic stiffness matrix of the pile, $\mathbf{\Psi}$ is the dynamic flexibility matrix of clamped-end piles for harmonic end displacements, $\mathbf{F_p}$ and $\mathbf{F_s}$ are, respectively, the flexibility matrix of the pile and the soil, $\mathbf{P_e}$ and $\mathbf{U_e}$ are the vector of external forces and displacements at the two ends of the pile, and $\mathbf{K_e}$ is the dynamic stiffness for the ensemble of piles.

In order to include the seismic analysis into this formulation, it is needed to express the displacement at each segment of the pile as the summation of seismic displacements in the medium when the piles are removed, and the displacements caused by pile-soil interface forces. Since the evaluation of the displacement of a soil with a cavity requires much more computational effort, it is assumed that the resulting cavity is filled with soil and the necessary modifications are included at the formulation. Such modifications allow seismic displacement in the soil mass with the cavities to be approximated by the associated free-field seismic displacements $\mathbf{U}^*$ due to a vertically propagating shear wave, which results

$$\mathbf{P_e} = \mathbf{K_e}\mathbf{U_e} + \bar{\mathbf{P}}_\mathbf{e}, \tag{2}$$

where $\bar{\mathbf{P}}_\mathbf{e} = -\mathbf{\Psi}^T(\mathbf{F_s} + \mathbf{F_p})^{-1}\mathbf{U}^*$ represents the fictitious forces which simulate the seismic effects at the pile ends. For more details about the derivation of the matrices involved in Eqs. (1) and (2), please refer to Kaynia and Kausel [10].

3 Results

In this section, the dynamic response of a pile group submitted to vertically propagating shear waves of circular frequency ω is investigated. It is assumed that these waves produce a free-field ground surface displacement $u_g^* = 1$. The results are presented in terms of the normalized frequency $a_0^2 = \omega^2\rho_s/\mu_s$ and the normalized complex-valued transfer function for the horizontal displacement $|u|/u_g^*$, which are presented in terms of their absolute values. In order to validate the present implementation, consider the example proposed by Kaynia and Kausel [10], which consists of a 3×3 pile group with $s/d_p = 5$ embedded in a homogeneous viscoelastic halfspace with $E_s = (E_p/100)$, $\beta_s = 0.05$, $\nu_s = 0.4$ and $\rho_s = 0.7\rho_p$, as shown in Fig. 2. For all the piles, the following parameters are used: $\beta_p = 0.0$, $\nu_p = 0.25$ and $l_p/d_p = 20$.

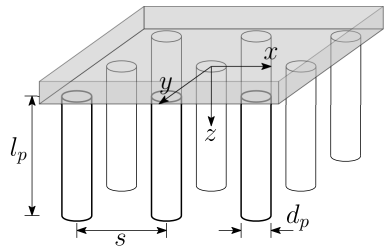

Figure 2. Model of a 3×3 pile group

Figure 3 shows the comparison between the transfer function in the foundation of the present and the Kaynia and Kausel's 1991 ("reference") implementation. The results show a good agreement with the present one.

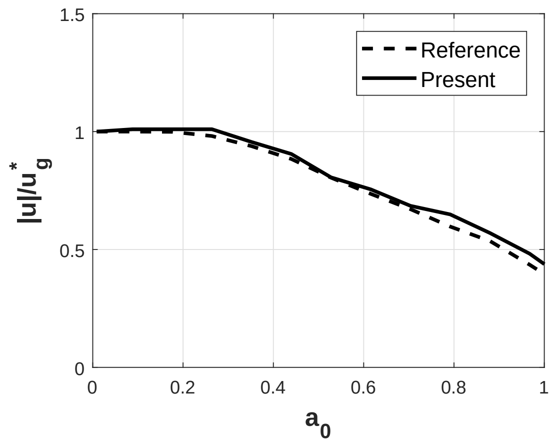

Figure 3. Transfer function for seismic response of 3×3 pile group

In order to investigate the seismic effects under the transfer function of the piled foundation system, the kinematic response for three parameters are analysed: the length of the pile l_p, the distance between adjacent piles s and the relation between the elasticity module of the soil and the pile E_s/E_p.

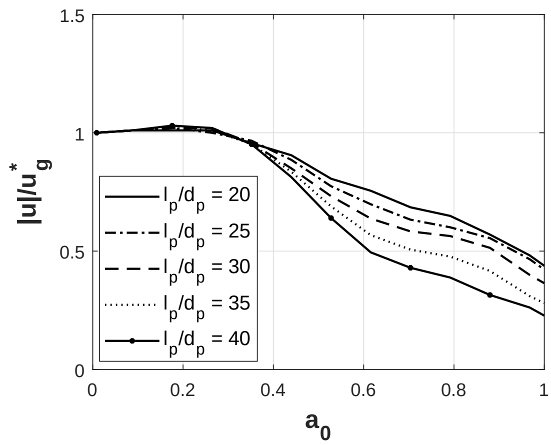

Figure 4. Transfer function for different values of pile length

Figure 4 shows the kinematic response of the pile group for a set of pile lengths. For low-frequency values, the transfer function approaches unity, which means that the foundation follows the ground motion for such frequencies. It can be also observed that the increase in the pile length tends to decrease the severity of the seismic excitation for a nondimensional frequency $a_0 > 0.4$.

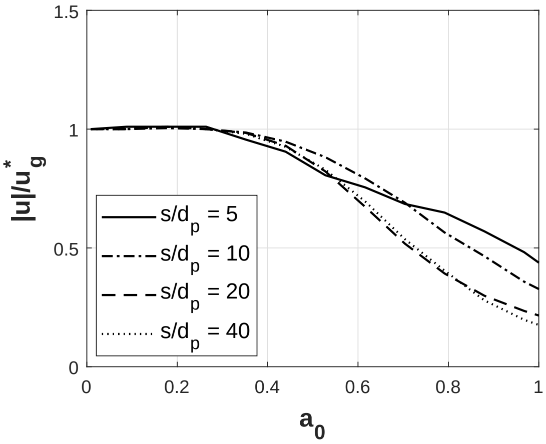

Figure 5. Transfer function for different values of pile spacing

Figure 5 presents the absolute value of transfer functions of the same pile group for different values of pile spacing. It can be noticed that the pile spacing significantly affects the kinematic response of the system for a nondimensional frequency $a_0 > 0.6$.

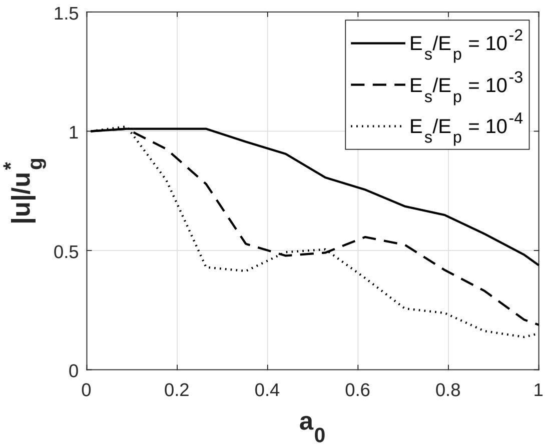

Figure 6. Transfer function for different values of elasticity modulus of the piles

Figure 6 shows the transfer functions for pile groups with different values of stiffness of the soil. Notice that the pile group embedded in a stiff soil ($E_s/E_p = 10^{-2}$) follows the ground motion for a larger range of frequencies. Also, it can be observed that the transfer function of the group tends to reduce as the soil becomes less rigid.

4 Conclusions

This paper presented an investigation of a pile group submitted to the seismic excitation from vertically propagating shear waves. The pile-soil interaction was modeled according to a well-established formulation available in literature. For such investigation, the transfer function of the group for different constitutive and geometric parameters were obtained and discussed. The results showed the high influence of these parameters on the kinematic response of the piled system.

5 Permission

The authors are the only responsible for the printed material included in this paper.

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