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Seismic response of piles and pile groups in viscoelastic and poroelastic soils

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Summary

This paper presents a simplified model to study the dynamic response of piles under seismic excitation. A coupled three dimensional Boundary Element-Finite Element model is considered to analyze the problem taking into account dynamic pile-soil-pile interaction. Piles and pile groups in a viscoelastic or poroelastic halfspace under various forms of seismic waves are considered.

Introduction

Seismic response of piles and pile groups in viscoelastic soil have received considerable attention in recent years. Several procedures to represent the pile-soil-pile system have been applied in this field. Generally, these methods allow for a better understanding of the system behavior and may provide results for the pile dynamic stiffness for forced vibrations and transfer functions for incident seismic waves. Nevertheless, there are difficulties for the analysis of large structures supported on piles using the existing methods. The model presented in this paper can be used to represent pile groups coupled to large structures (like bridges or buildings) using a reasonable number of degrees of freedom.

Dynamic behavior of poroelastic soils has also received attention in recent times with important contributions to a proper understanding of their influence on some soil-structure interaction problems. However, very few studies have been presented where dynamic compliances or transfer functions for seismic wave excitation, for piles and pile groups in poroelastic soils are computed. The seismic response of piles and pile groups, considering the soil as a uniform two-phase fluid-saturated poroelastic medium, is studied in the present paper.

Basic formulation

A structure (including piles) is discretized into 3D beam-type finite elements with distributed mass. The material is linear elastic with internal damping of hysteretic type. Dynamics equations of the motion are formulated in the frequency domain. The equilibrium system of equation can be written as

$$\begin{pmatrix} S_{ss} & S_{sb} & S_{pb} \\ S_{bs} & S_{bb} & S_{bp} \\ S_{ps} & S_{pb} & S_{pp} \end{pmatrix} \begin{pmatrix} u_s^t \\ u_b^t \\ u_p^t \end{pmatrix} = \begin{pmatrix} P_s \\ P_b \\ P_p \end{pmatrix} \tag{1}$$

where s denotes non-connected superstructure nodes, b connected nodes (pile-structure interface), and p denotes nodes along the pile.

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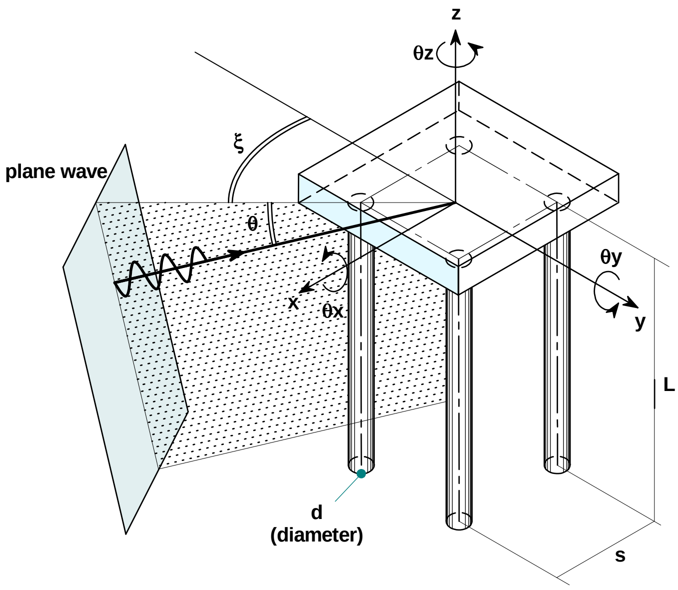

Figure 1: Pile foundation under seismic excitation

Load amplitudes are represented by P, and $P_T = P + P_0$ is the summation of the interaction forces with the soil and the directly-applied forces on nodes of the structure or pile. Total displacements are denoted by superscript t. Equilibrium conditions along impervious viscoelastic-poroelastic (pile-soil) interface are:

$$P = -MFpil.T = -MFpil.(t + \tau) = -MFpil.(t + \phi.p) \tag{2}$$

where T denote total traction on the poroelastic medium , p pore pressure and ϕ porosity, and MFpil the transformation matrix between forces and tractions. Both conditions are included in the global expression

$$P = -MFpil.t = \begin{pmatrix} -MFpil_{cp} & 0 \\ 0 & -MFpil_p \end{pmatrix} \begin{pmatrix} t_{cp} \\ t_p \end{pmatrix} \tag{3}$$

where P denotes the force on the nodes of the pile and t_{cp} and and t_p denote the tractions over the head and along the pile respectively.

Three dimensional quadratic boundary elements are used to model the soil surface. A simplified two-node cylindrical boundary element, similar to that developed by Coda et al. [4], has been implemented to model the soil surface in touch with the piles. Nodes of these cylindrical elements are located at the axis. Nodal variables represent displacement and traction values over the cylindrical surface. They have a linear variation along z and are constant along the perimeter.

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The classical BE system of equations can be written as

$$\begin{pmatrix} H_{cp} & H_p & H_g & H_{gp} \end{pmatrix} \begin{pmatrix} u_{cp} \\ u_p \\ u_g \\ u_{gp} \end{pmatrix} = \begin{pmatrix} G_{cp} & G_p & G_g & G_{gp} \end{pmatrix} \begin{pmatrix} t_{cp} \\ t_p \\ t_g \\ t_{gp} \end{pmatrix} \tag{4}$$

where u and t are displacement and traction values, respectively, and H and G the BEM coefficient matrices. The subscripts g and gp denote the ground surface nodes non-connected and connected to the pile head, respectively; cp and p denote the pile head nodes and the nodes along the pile, respectively.

Using compatibility conditions at the pile cap, and adding rows of cp and gp displacements one obtains:

$$\begin{pmatrix} (H_{cp}+H_{gp})*D & H_p & H_g & -G_{cp} & -G_p \end{pmatrix} \begin{pmatrix} u_{ref} \\ u_p \\ u_g \\ t_{cp} \\ t_p \end{pmatrix} = \begin{pmatrix} G_{gp}t_{gp} \\ G_g t_g \end{pmatrix} \tag{5}$$

where matrix D relates head pile head displacements with displacements at the centre of stiffness of a pile group (u_{ref}).

A set of coupled finite and boundary elements equations can be written as follows:

$$\begin{pmatrix} S_{ss} & S_{sb}D & S_{pb} & 0 & 0 & \\ D^T S_{bs} & D^T S_{bb} D & D^T S_{bp} & 0 & D^T MFpil_b & 0 \\ S_{ps} & S_{pb}D & S_{pp} & 0 & 0 & MFpil_p \\ 0 & (H_{cp}+H_{gp})*D & H_p^{orl} & H_g & -G_{cp} & -G_p \end{pmatrix} \begin{pmatrix} u_s^t \\ u_{ref}^t \\ u_p^t \\ u_g^t \\ t_{ref} \\ t_p \end{pmatrix} = \begin{pmatrix} P_s \\ D^T P_{b0} \\ P_{p0} \\ G_{gp}t_{gp} \\ G_g t_g \end{pmatrix} \tag{6}$$

where matrix H_p have been completed to H_p^{orl} with columns of zeros corresponding to rotation's degrees of freedom in u_{ref}.

Numerical studies

Two types of numerical studies, corresponding to viscoelastic and poroelastic soil, have been carried out. In order to validate the model, the seismic response of a single pile and a 3x3 pile group embedded in a viscoelastic halfspace is considered first (fig. 1 and fig. 2). For the sake of brevity, only results for SH waves impinging on the foundation with an arbitrary angle from the vertical axis are presented.

The transfer functions presented herein correspond to pile foundations with $\rho_p/\rho_s = 3/2, \nu_p = 0.25, \nu_s = 0.33, \beta_p = 0.0, \beta_s = 0.05, E_p/E_s = 1000$ and L/d=20. The piles in a group are spaced s=5d

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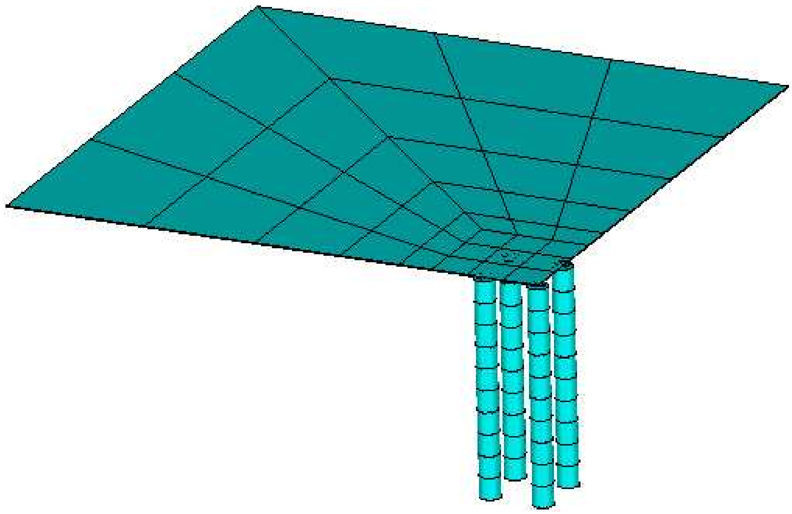

Figure 2: Double-symmetric model discretization of 3x3 pile group

The obtained results for displacement transfer functions are showed in fig. 3 and fig. 4. A very good agreement with those obtained by Kaynia and Novak [1] can be observed.

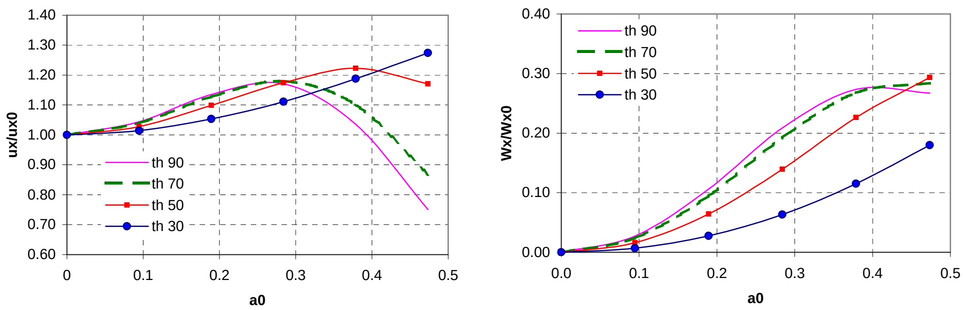

Figure 3: Transfer functions for horizontal displacement and rocking of single piles under SH waves. Viscoelastic soil.

For the case of piles in a poroelastic halfspace, vertically incident SH waves have been considered. Properties considered for the soil are $\mu = 3.2175e7 N/m^2, \nu_s = 0.25, \rho_s = 1425 kg/m^3, \rho_f = 1000 kg/m^3, \rho_a = 0., \phi = 0.35, b = 3.0e7 N/m^2, Q = 4.61e8 N/m^2, R = 2.4823e8 N/m^2$ and for de piles$Ep/E_{drained} = 343, \rho_p/\rho_{bulkmaterial} = 1.94, \nu_p = 0.20$. Impervious contact between piles and soil has been considered.

The differences between the poroelastic model and two limit cases, drained and undrained

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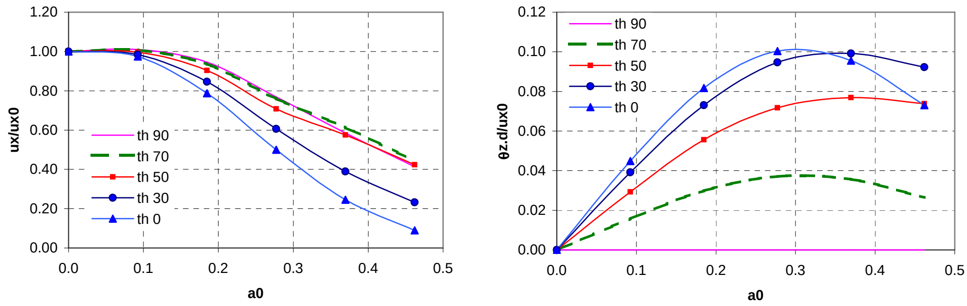

Figure 4: Transfer functions for horizontal displacement and torsion of 3x3 pile group under SH waves. Viscoelastic soil.

equivalent viscoelastic soils, are analyzed. The influence of parameter b (dissipation constant) is also studied. The obtained results are plotted versus dimensionless frequency $a_0 = \omega.d/c_s$ in fig. 5 and fig. 6 for the single pile and the pile group, respectively.

Differences between results obtained with various models are not important for low frequency values. However, the influence of b parameter becomes important when the frequency increases. Displacement values at pile head are significantly larger for b=0. and b=3.e4 than for any other case, when $a_0 \geq 0.3$.

Pile response does not show an homogeneous behavior with b. Incident wave displacement for high values of b (3.0e7) are similar to those of an equivalent drained or undrained viscoelastic medium. So, transfer function are similar too. For medium and small values of b (3.0e4 and 0.), incident wave displacements differ from those of the viscoelastic half-space because shear the wave velocity has a 20% difference with respect to the equivalent viscoelastic medium when $b \leq 3.0e5$. This change modifies the free field displacement and, as a result, the final displacement of the pile.

Differences between b=3.e4 and b=0 are caused by effects of dissipation in wave amplitude. Since a free field displacement amplitude at ground surface has been assume, wave amplitude at a certain depth may have very different values depending on dissipation. This fact gives rise to greater displacement values for b=3.e4 than for b=0.

It can be concluded that viscoelastic equivalent model results are in good agreement with those of the poroelastic soil for high values of b (low permeability), but not for low values (high permeability).

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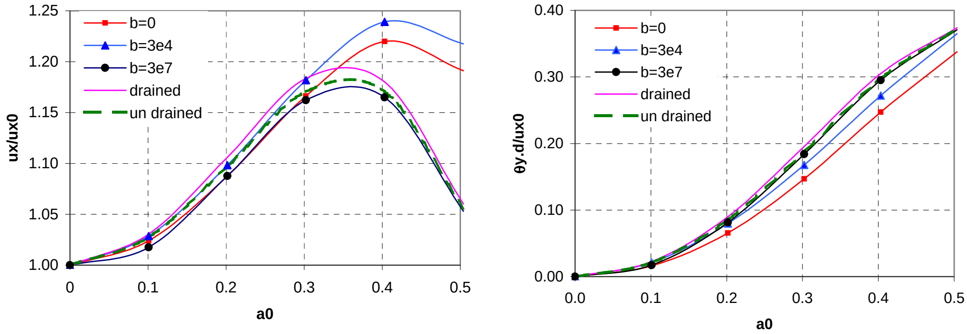

Figure 5: Transfer functions for horizontal displacement and rocking of single piles under vertical SH waves. Poroelastic soil.

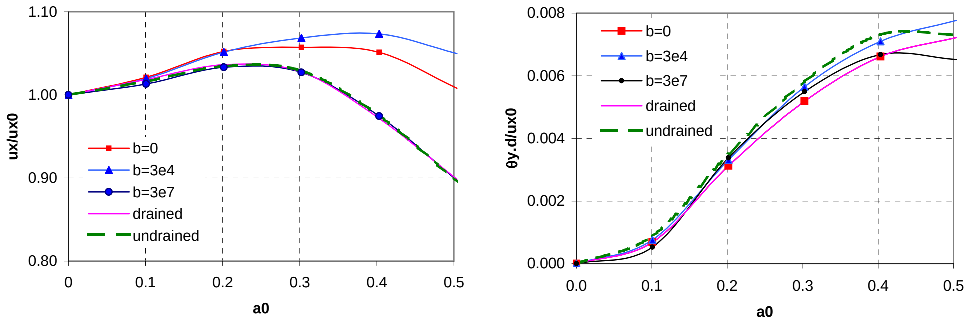

Figure 6: Transfer functions for horizontal displacement and rocking of 3x3 pile group under vertical SH waves. Poroelastic soil.

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