Computers and Geotechnics 85 (2017) 249–261

Contents lists available at ScienceDirect

Computers and Geotechnics

journal homepage: www.elsevier.com/locate/compgeo

Research Paper

A hybrid element method for dynamics of piles and pile groups in transversely isotropic media

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ARTICLE INFO

Article history:
Received 16 August 2016
Received in revised form 13 November 2016
Accepted 24 December 2016

Dedicated to the Memory of Dr. Asadollah Noorzad.

Keywords:
Hybrid element method
Pile group
Transversely isotropic
Elasto-dynamics
Soil-structure interaction

ABSTRACT

A hybrid analytical-numerical method is proposed for the dynamic analysis of single piles and pile groups embedded in semi-infinite transversely isotropic media. In the method proposed, the soil-pile system is modeled using finite elements combined with massless rigid radiation discs representing pile-soil-pile interaction. The elasto-dynamic response of the radiation discs buried at different depths in a transversely isotropic half-space is analytically derived in a transform domain using a set of complete potential functions. A Boussinesq-type loading distribution is introduced to act on the disc region to achieve the proper mode of deformation at the cross sections of piles. Numerical results and comparisons with known analytical/numerical solutions are presented, demonstrating the application of the method.

1. Introduction

Dynamics of single piles and pile groups has been the subject of extensive attention in the past few decades due to their wide spread applications in structures exposed to dynamic loading such as offshore platforms, bridges, and machinery foundations. A variety of numerical and analytical techniques has been developed to investigate the behaviour of piles and pile groups [1–16], including the effects of excitation frequency, group size and configuration, pile spacing, pile slenderness ratio, and mechanical properties of piles and soil. However, the influence of soil anisotropy is often neglected due to the inherent complexities associated with the behaviour of anisotropic materials.

Perhaps the most common form of anisotropy observed in geological formations is the transverse isotropy with a vertical axis of symmetry. The earliest dynamic studies of transversely isotropic media are due to Stoneley [17], Synge [18], Buchwald [19] and Payton [20], who demonstrated fundamental differences between wave propagation in anisotropic and isotropic media. For piles embedded in transversely isotropic media, Liu and Novak [21] proposed a numerical method based on the Green's functions for ring loads obtained from the solution of thin layers underlain by a rigid base [22]. Wang and Rajapakse [23] examined the dynamic response of rigid massless cylindrical and hemispherical foundations embedded in transversely isotropic half-space using the boundary element method. In their method, the elasto-dynamic Green's functions of the half-space subjected to ring loads were derived using three potential functions [24] which may not provide the complete solution of the equations of motion [25]. Using the same Green's functions, Barros [26,27] obtained the influence functions of the medium for distributed loads and proposed an indirect boundary element method for the analysis of cylindrical foundations in transversely isotropic soil. In this work, the load distribution along the elements was assumed to be uniform and the coupling between pile and soil was enforced at the center of the elements, which can lead to displacement incompatibility in soil-pile interaction problems [28]. More recently, fundamental solutions have been developed for the load-transfer analysis of single piles in transversely isotropic media under vertical and transverse excitations. Shahmohamadi et al. [29,30] derived the mathematical formulation for the analysis of elastic cylindrical thin-walled piles subjected to vertical dynamic excitations using shell theory for the pile and a set of ring-load Green's functions for the embedding medium. Gharahi et al. [31] proposed a fundamental solution for dynamic, laterally loaded single piles following the approach proposed by Pak and Jennings [32] in which the interaction problem

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http://dx.doi.org/10.1016/j.compgeo.2016.12.029
0266-352X/

was formulated by a Fredholm integral equation of the second kind. The fundamental solutions developed are mainly limited to the analysis of single piles under specific loading conditions and cannot be readily extended to the pile-soil-pile interaction problems or the problems with more complex loading and boundary conditions.

The main objective in this paper is to present a computationally efficient numerical-analytical method for the rigorous three-dimensional dynamic analysis of piles and pile groups embedded in semi-infinite transversely isotropic media, overcoming the deficiencies highlighted above. In the approach proposed, the piles are modeled using conventional finite elements, while novel rigid massless elements, referred to as radiation discs, are introduced to model dynamic pile-soil-pile interaction and to deal with infinite domains. The complete proof of the theoretical underpinning of the proposed method is presented in the paper. The dynamic response of the radiation discs buried at different depths in a transversely isotropic half-space is analytically derived in a transform domain using a set of complete potential functions proposed by Eskandari-Ghadi and Noorzad [25,33]. In dynamic pile-soil interaction analyses, the selection of proper loading configuration and compatibility condition is crucial to obtain accurate solutions [28]. A Boussinesq-type loading distribution is introduced to act on the disc region to achieve the proper mode of deformation at the cross sections of piles. In the method proposed, the discretization is only required along the length of piles, while the discretization of surrounding medium, top free surface boundary, and cross sections of piles are avoided, yielding a significant computational saving, in particular when the group consists of a large number of piles. Numerical results and comparisons with known analytical/numerical solutions are presented to demonstrate the accuracy and convergence of the present solution scheme. The influence of excitation frequency, pile spacing, and soil anisotropy on horizontal and vertical compliances of pile groups is particularly emphasized.

2. Hybrid element method

The soil-pile group system considered in this study is shown in Fig. 1, in which Ω_P and Ω_S denote the regions of the three-dimensional (visco)elastic space occupied by cylindrical piles and the surrounding medium, respectively. The common boundary of the regions is designated by Γ. The piles are assumed to be fully embedded in, and continuously bonded to the medium. Cartesian coordinate system is used as the global coordinate for the whole soil-pile group system. Using the conventional indicial notation, the equations of motion and the displacement-stress relations governing the system can be written as

$$\sigma_{\alpha ji,j} + f_{\alpha i} = \rho_\alpha \ddot{u}_{\alpha i} \quad \text{on } \Omega_\alpha \quad (\alpha = P, S) \tag{1}$$

$$\sigma_{\alpha ij} = \frac{C_{\alpha ijkl}}{2}(u_{\alpha k,l} + u_{\alpha l,k}) \quad \text{on } \Omega_\alpha (\alpha = P, S) \tag{2}$$

where $\sigma_{\alpha ij}$ is the Cauchy stress tensor, $u_{\alpha i}$ is the displacement vector, $\ddot{u}_{\alpha i}$ is the acceleration vector, $f_{\alpha i}$ is the body-force density vector, $C_{\alpha ijkl}$ is the stiffness tensor, ρ_α is the density, and the subscripts P and S denote the corresponding quantities of the pile region and the surrounding medium, respectively. These field equations are subjected to the displacement and traction boundary conditions, i.e.

$$u_{Pi} = u_{Si}, \quad (\sigma_{Pji} - \sigma_{Sji})n_j = 0 \quad \text{on } \Gamma \tag{3}$$

where n_j is the unit outward normal vector of Γ. Provided the soil-pile group system is linear, it can be decomposed into a soil medium and a pile group system [34,35,32], see Fig. 2. In the soil medium, the same material as the embedding soil is assumed to occupy the pile region Ω_P, while the pile group system is introduced throughout Ω_P such that the superposition of the systems in the pile region gives the same material properties as the actual embedded piles. Using the principle of superposition, the governing equations (1)–(3) can be decomposed into:

For the soil medium:

$$\begin{cases} \sigma_{Sji,j} + f_{Si} = \rho_S \ddot{u}_{Si} & \text{on } \Omega_S \\ \sigma^e_{Pji,j} + f^e_{Pi} = \rho_S \ddot{u}_{Pi} & \text{on } \Omega_P \end{cases} \tag{4}$$

$$\begin{cases} \sigma_{Sij} = \frac{C_{Sijkl}}{2}(u_{Sk,l} + u_{Sl,k}) & \text{on } \Omega_S \\ \sigma^e_{Pij} = \frac{C_{Sijkl}}{2}(u_{Pk,l} + u_{Pl,k}) & \text{on } \Omega_P \end{cases} \tag{5}$$

$$u_{Pi} = u_{Si}, \quad (\sigma^e_{Pji} - \sigma_{Sji})n_j = T^e_i \quad \text{on } \Gamma \tag{6}$$

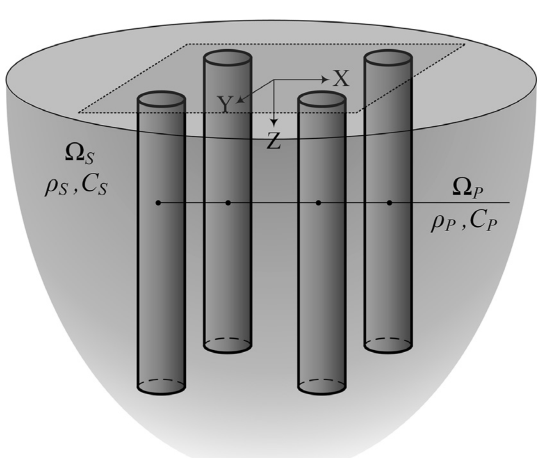

Fig. 1. Three-dimensional pile-soil-pile system.

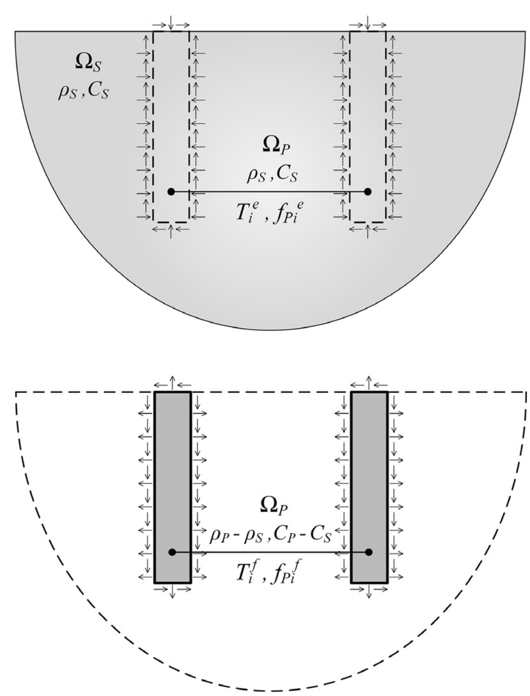

Fig. 2. Decomposition of the pile-soil-pile system using the principle of superposition: the soil medium (above), the pile group system (below).