Computers and Geotechnics 89 (2017) 195–202

Contents lists available at ScienceDirect

Computers and Geotechnics

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

Research Paper

Effect of compressible parameters on vertical vibration of an elastic pile in multilayered poroelastic media

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ARTICLE INFO

Article history:
Received 19 January 2017
Received in revised form 12 April 2017
Accepted 2 May 2017

Keywords:
Compressible parameters
Vertical vibration
Axially loaded pile
Multilayered poroelastic soils
Finite element method
Analytical layer-element method

ABSTRACT

This paper mainly investigates the influences of compressible parameters on the vertical vibration of a pile embedded in layered poroelastic soil media. The pile is treated as a 1D elastic bar by the finite element method, and fundamental solutions for the layered poroelastic soils due to a vertical dynamic load are obtained by the analytical layer element method. Based on the compatibility conditions, the pile-soil dynamic interaction problem is solved. The numerical scheme has been compiled into a Fortran program for numerical calculation. Influences of the pile-soil stiffness ratio, compressible parameters, vibration frequency and the soil stratification are discussed.

1. Introduction

With the wide application of pile foundations in geotechnical engineering, the pile-soil interaction problem due to dynamic loadings has gained extensive attentions from researchers for the past decades. As far as we know, for the cases where there exists fluid in the medium, it is more reasonable to assume the medium is poroelastic. Therefore, the study of the pile foundation embedded in two-phased poroelastic soils is of significant value in engineering practice. Recent developments in the field of dynamic response of two-phased poroelastic soils have their roots back in the classical works by Biot [1–3], who developed the theory of wave propagation in a fluid-filled, poroelastic saturated media and extended his theory to include anisotropy, viscoelasticity and solid dissipation. Thereafter, more researchers [4–13] considered the problems related to dynamic response of a single poroelastic soil layer or a poroelastic half-space under external loadings, and some researchers considered more complicated situations with the soil stratification [14–20]. These studies have laid a solid foundation for the investigation of pile-structure interaction problems due to dynamic loadings.

A review of the literature indicates that the study of the dynamic interaction problem of a pile and the poroelastic soil has received wide attentions over the past few years. Zeng and Rajapakse [21] firstly studied the vertical vibration of a single pile embedded in a poroelastic medium. Lu and Jeng [22] and Lu et al. [23,24] presented several works on the pile's dynamic response in a poroelastic soil. These works [21–24] mainly applied the extended Muki and Sternberg method, by which the pile is modeled as a 1D bar and formulated by the second kind Fredholm integral equation. Wang et al. [25] developed solutions for the torsional vibration of an end bearing pile embedded in a poroelastic soil. Zheng et al. [26] extended Cai and Hu's [27] solution to the analysis of the vertical vibration of an elastic pile embedded in a poroelastic soil. Moreover, several studies [28–30] of dynamic response of a pile group embedded in a poroelastic soil have been published. However, none of the above investigations included influences of Biot's parameters for compressibility of two-phased poroelastic soils on the dynamic response of a vertically loaded pile embedded in a layered poroelastic soil media.

The main objective of this paper is to study influences of Biot's compressibility parameters on the pile-soil dynamic interaction problem. In this study, similar to the former work for the pile-soil interaction problem due to static loads by the authors [31] the pile is also treated as a 1D elastic bar and discretized by applying the finite element method. Fundamental solutions for the layered poroelastic soils underlying a subjacent stratum-rock subjected to dynamic unit load are obtained by Ref. [32], where the influences of Biot's compressibility parameters of soil grains

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http://dx.doi.org/10.1016/j.compgeo.2017.05.002
0266-352X/

and pore fluid on multilayered poroelastic soils under harmonic loadings have been investigated. Taking into consideration the compatibility conditions, the pile-soil interaction problem due to vertical harmonic loadings can be solved. The numerical scheme is compiled into a Fortran program for calculation. Numerical examples are implemented to investigate influences of the pile-soil stiffness ratio, compressible parameters, vibration frequency and the soil stratification on the pile- poroelastic soil dynamic interaction problem.

2. Solution for the multilayered poroelastic soils

In this paper, an n-layered poroelastic soil system is considered as shown in Fig. 1. G, λ, ρ are the shear modulus, Lame's constant and soil density, respectively; ρ_f and k are the fluid density and permeability, respectively; h is the thickness of soil layer; α and M are the Biot's parameters for compressibility of soil grains and pore fluid. A time-harmonic load $Pe^{i\omega t}$ with a radius $\tilde{r}$ is applied in the interior of the soils.

According to Ref. [32], the global stiffness matrix for the multilayered poroelastic soils bonded to a rigid base is established as

$$\begin{bmatrix} -\bar{\mathbf{V}}(\xi,0) \\ \mathbf{0} \\ \vdots \\ -\bar{\mathbf{F}}(\xi,H_i) \\ \mathbf{0} \\ \vdots \\ \bar{\mathbf{V}}(\xi,H_m) \end{bmatrix} = \begin{bmatrix} \boldsymbol{\Phi}^{(1)} & & & \mathbf{0} \\ & \boldsymbol{\Phi}^{(2)} & & \\ & & \ddots & \\ & & \boldsymbol{\Phi}^{(m-1)} & \\ \mathbf{0} & & & \boldsymbol{\Phi}^{(m)} \end{bmatrix}_{(3m+3)\times(3m+3)} \begin{bmatrix} \bar{\mathbf{W}}(\xi,H_0) \\ \bar{\mathbf{W}}(\xi,H_1) \\ \vdots \\ \bar{\mathbf{W}}(\xi,H_i) \\ \vdots \\ \bar{\mathbf{W}}(\xi,H_{m-1}) \\ \bar{\mathbf{W}}(\xi,H_m) \end{bmatrix}, \tag{1}$$

where $\bar{\mathbf{V}}(\xi,z) = [\bar{\sigma}_{rz} \quad \bar{\sigma}_z \quad \bar{Q}]^T$, $\bar{\mathbf{W}}(\xi,z) = [\bar{u} \quad \bar{w} \quad \bar{p}]^{\mathrm{T}}$; $\bar{\sigma}_{rz}$, $\bar{\sigma}_z$, $\bar{Q}$ denote shear stress in the plane r-z, the normal stress of solid matrix in the $z = 1,\dots,n-1$ direction and flow quantity through unit cross section area in the Hankel transformed domain, separately; $\bar{u}$, $\bar{w}$, $\bar{p}$ are the displacement components of soil grains in the r and z directions and pore pressure in the Hankel transformed domain, respectively; $\bar{\mathbf{F}}(\xi,H_i)$ is the vertical load vector acting at depth H_i in the Hankel transformed domain; $\Phi^{(m)}$ is the analytical element for the mth layer and detailed elements of Φ can be found in Ref. [32]. To accomplish the Hankel inverse transform, we compile a corresponding Fortran program based on the Gauss-Legendre quadrature suggested by Ai et al. [33]. Solutions in the frequency domain are further obtained.

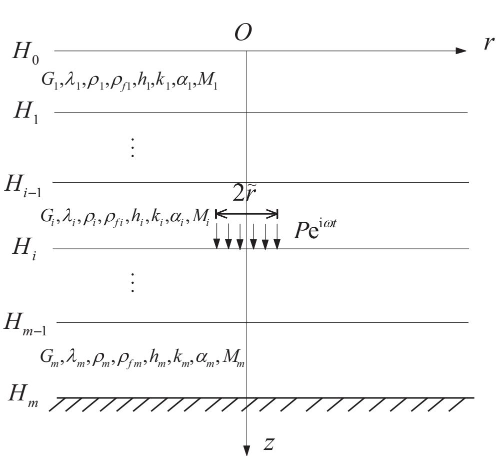

Fig. 1. Multilayered poroelastic soils subjected to a vertical load.

3. Analysis of the pile

Fig. 2 shows a pile in a multilayered poroelastic soil system bonded to a rigid base due to a time-harmonic load $P_0e^{i\omega t}$ and the term $e^{i\omega t}$ is omitted in the derivation. The pile is supposed to be an elastic cylinder with length l and diameter d. With the assumption of negligible radial deformation, the pile in this study is modeled as a 1D bar and equally divided into n elements. Due to the finite element method, the stiffness matrix of a pile element i $(i = 1, 2, 3 \dots n)$ is

$$[\mathbf{K}_p]_i = \frac{E_i \cdot A_i}{\Delta l_i} \cdot \begin{bmatrix} 1 & -1 \\ -1 & 1 \end{bmatrix}, \tag{2}$$

where A_i, E_i and Δl_i are the cross-sectional area, Young's modulus and the length of the pile element i, respectively.

Taking into account the pile's properties of continuity and uniformity, the global stiffness matrix of the single pile is established as

$$\mathbf{K}_p = \frac{E_i \cdot A_i}{\Delta l_i} \begin{bmatrix} 1 & -1 & 0 & 0 & \cdots & \cdots & 0 & 0 \\ -1 & 2 & -1 & 0 & \cdots & \cdots & 0 & 0 \\ 0 & -1 & 2 & -1 & \cdots & \cdots & 0 & 0 \\ 0 & 0 & -1 & 2 & \cdots & \cdots & 0 & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & \cdots & \cdots & -1 & 2 & -1 & 0 \\ 0 & 0 & \cdots & \cdots & 0 & -1 & 2 & -1 \\ 0 & 0 & \cdots & \cdots & 0 & 0 & -1 & 1 \end{bmatrix}_{(n+1)\times(n+1)}. \tag{3}$$

According to Ref. [34], the general equation of motion for the pile in the absence of internal damping is written as

$$\mathbf{M}\ddot{\mathbf{u}}_p(t) + \mathbf{K}_p\mathbf{u}_p(t) = \mathbf{F}_p(t), \tag{4}$$

where $\mathbf{M} = \frac{\rho_p A_i \Delta l_i}{6} \begin{bmatrix} 2 & 1 & 0 & 0 & \cdots & \cdots & 0 & 0 \\ 1 & 4 & 1 & 0 & \cdots & \cdots & 0 & 0 \\ 0 & 1 & 4 & 1 & \cdots & \cdots & 0 & 0 \\ 0 & 0 & 1 & 4 & \cdots & \cdots & 0 & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & \cdots & \cdots & 1 & 4 & 1 & 0 \\ 0 & 0 & \cdots & \cdots & 0 & 1 & 4 & 1 \\ 0 & 0 & \cdots & \cdots & 0 & 0 & 1 & 2 \end{bmatrix}_{(n+1)\times(n+1)}$ is the mass matrix of the pile; $\mathbf{u}_p(t) = [u_0^p e^{i\omega t}, u_1^p e^{i\omega t}, \dots, u_n^p e^{i\omega t}]^{\mathrm{T}}$ is the nodal displacement vector of the pile, $\ddot{\mathbf{u}}_p(t)$ denotes the second

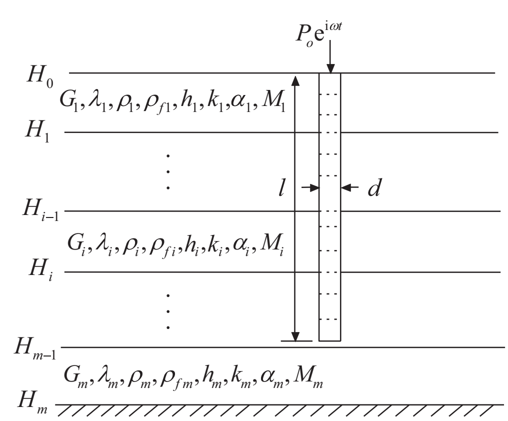

Fig. 2. A single pile embedded in a multilayered poroelastic soil system.