Soil Dynamics and Earthquake Engineering 111 (2018) 184–192

Contents lists available at ScienceDirect

Soil Dynamics and Earthquake Engineering

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

Horizontal impedances of saturated soil layer with radially inhomogeneous boundary zone

Anfeng Hu[a,b], Peng Fu[a,b,*], Changqing Xia[a,b], Kanghe Xie[a,b]

[a] MOE Key Laboratory of Soft Soils and Geoenvironmental Engineering, Zhejiang University, Hangzhou, China
[b] Research Center of Coastal and Urban Geotechnical Engineering, Zhejiang University, Hangzhou, China

ARTICLE INFO

Keywords:
Horizontal
Dynamic impedances
Boundary zone
Saturated soil
Transfer matrix method

ABSTRACT

The dynamic impedance of saturated soil layer with a radially inhomogeneous boundary zone to horizontally vibrating pile is theoretically investigated. A continuous, radial variation for the soil properties is assumed, so that there are no wave reflections from the fictitious interface. For the purpose of analysis, the inhomogeneous boundary zone is subdivided into a series of concentric annular sub-zones with constant material properties. The impedances of soil are obtained by adopting transfer matrix method. To verify the solution obtained herein, the computed results are compared with those obtained from earlier solution. Then, a parameter study is performed to investigate the effect of parameters involved. It is found that variations in shear modulus and the width of boundary zone have significant influence on the soil impedances.

1. Introduction

The interaction between surrounding soil and the pile significantly affects the dynamic response of the pile. How to model the soil accurately is an important research topic in the dynamic analysis of pile foundation. In the past decades, many research studies have been performed to investigate the pile-soil interaction. Novak [1] and Novak et al. [2] proposed a simple and efficient model for analyzing the resistance of soil to pile vibration. This model assumed no strain in the vertical direction; hence the soil is divided into a series of thin uncoupled horizontal layers in the analysis. Nogami and Novak [3,4] developed more rigorous solution procedure to analyze the horizontal resistance of soil to pile vibration. Mylonakis [5] developed an improved model to investigate the soil reaction to large-diameter piles. The model retains the simplicity of the plane strain model while accounting for the three-dimensional effects. Anoyatis et al. [6] presented a revised 3D continuum modeling to investigate the soil reaction to lateral harmonic pile motion. These studies are usually based on the assumption that the soil layers are homogeneous medium with uniform properties. However, the soil properties adjacent to the pile usually change due to construction disturbance and degradation of modulus under cyclic loading. Many studies have shown that the dynamic response of the pile is very sensitive to the soil properties in the vicinity of the pile [7,8].

To investigate the effect of variation in material properties of soil adjacent to the pile, Novak and Sheta [9] introduced a weakened annular boundary zone, but the mass of boundary zone is neglected. Lakshmanan and Minai [10] and Veletsos and Dotson [11] later developed an improved model that account for the mass of the boundary zone for horizontal vibration of soil layer. Novak and Han [12] further found that a homogeneous boundary zone with a nonzero mass can cause significantly undulatory variations of the impedances due to wave reflections from the interface between the two zones. Then, Han and Sabin [13] presented a new model in which the shear modulus of boundary zone varies in parabolic form. El Naggar [14] developed a method to analyze the impedance of radially inhomogeneous soil layers in which the soil media is modeled as a series of springs. Karatzia et al. [15] investigated horizontal soil reaction to a cylindrical pile segment surrounded by an annular zone of soft material. Wang et al. [16] and Wu et al. [17] developed more efficient model to analyze the vertical and torsional impedance of radially inhomogeneous soil.

In the aforementioned studies, the surrounding soil of the pile is mostly assumed as a single-phase medium. In fact, the soil is usually a porous medium consisting of solid skeleton and pore fluid. Thus, it is not appropriate to evaluate the impedances of porous medium by adopting the aforementioned model. Biot [18] developed an elastodynamic theory for fluid-saturated porous medium. Based on Biot's theory and plane strain model [1,2], Shang et al. [19] presented an analytical solution for the horizontal impedance of saturated soil to the pile. Xu et al. [20] analyzed the dynamic response of piles in poroelastic half-space by using the Muki and Sternberg's method. Li et al. [21] investigated the vertical impedance of piles embedded in saturated soil.

* Corresponding author at: MOE Key Laboratory of Soft Soils and Geoenvironmental Engineering, Zhejiang University, Hangzhou, China.
E-mail address: fupeng@zju.edu.cn (P. Fu).

https://doi.org/10.1016/j.soildyn.2018.04.012
Received 18 March 2017; Received in revised form 3 April 2018; Accepted 7 April 2018
0267-7261/

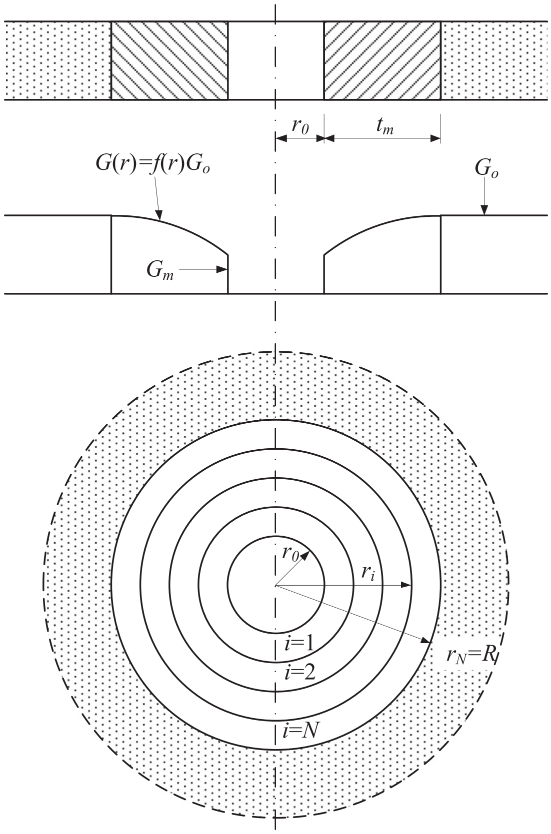

Fig. 1. Model of composite soil layer with radially inhomogeneous boundary zone.

Wang et al. [22] investigated the torsional impedances of the pile in saturated soil. Although many studies have been performed, the research on the influence of radial inhomogeneity of saturated soil layer on the dynamic impedance is still insufficient.

In this paper, an efficient analytical approach is proposed to evaluate the horizontal impedances of saturated soil layer with radially inhomogeneous boundary zone. A continuous variation in material properties of the boundary zone is assumed, so that wave reflections from the fictitious interface can be avoided. The radially inhomogeneous boundary zone is divided into a series of concentric annular sub-zones with constant material properties. The horizontal impedances of soil are obtained through transfer matrix method [23,24] based on plane strain model. The validity and accuracy of present solution is verified by comparing with those for homogeneous layers as well as for radially inhomogeneous layers of single-phase medium.

2. Model description

To investigate the effect of radial inhomogeneity of saturated soil, the soil layer is assumed as a composite layer. As shown in Fig. 1, the composite layer is composed of two concentric zones: an outer semi-infinite undisturbed zone and an inner boundary zone with disturbed material. The outer zone medium is assumed to be homogeneous. Within the inner boundary zone, the complex shear modulus $G^*(r)$ is assumed to vary continuously, so that there are no wave reflections from the interface between the inner zone and outer zone. The complex shear modulus $G^*(r)$ of the composite medium is given by the expression

$$G^*(r) = \begin{cases} G_m^* & r = r_0 \\ G_o f^*(r) & r_0 < r < R \\ G_o^* & r \geq R \end{cases} \tag{1}$$

in which

$$G_m^* = G_m(1 + \mathrm{i}\delta_m)$$
$$G_o^* = G_o(1 + \mathrm{i}\delta_o) \tag{2}$$

where G_m and G_o are the shear modulus of the soil at the pile-soil interface and the outer zone, respectively; δ_m and δ_o are the material damping of the soil at the same locations, respectively; r_0 is the radius of the pile segment; R is the radius of the interface of the inner and outer zones; r is the radial distance to an arbitrary point. The variation of material properties within the inner boundary zone is described by the function $f^*(r)$. According to the research of Han and Sabin [13] and El Naggar [14], the function $f^*(r)$ employed in this paper is expressed as

$$f^*(r) = f_G(r)(1 + \mathrm{i}\delta_r) \tag{3}$$

$$\delta_r = f_\delta(r)\delta_o \tag{4}$$

in which

$$f_G(r) = 1 - \left(\frac{R - r}{t_m}\right)^p \left(1 - \frac{G_m}{G_o}\right) \tag{5a}$$

$$f_\delta(r) = 1 - \left(\frac{R - r}{t_m}\right)^q \left(1 - \frac{\delta_m}{\delta_o}\right) \tag{5b}$$

where $f_G(r)$ and $f_\delta(r)$ describe the continuous variation of the soil modulus and material damping within the inner boundary zone, respectively; t_m is the width of inner boundary zone.

It is not possible to obtain a solution for the impedances of soil layer with such complicated radial variation in the material properties directly. Hence, the inner boundary zone is subdivided into N concentric annular sub-zones. The radius of the outer boundary of the ith annular sub-zone is denoted by r_i. Each sub-zone is considered to be homogeneous with constant complex shear modulus G_i^*, which is determined from Eqs. (1)–(5) with the pertinent radius r_i. The displacements and stresses at the interface between the two adjacent sub-zones are assumed to be continuous.

3. Governing equations and analytical solutions

3.1. Governing equations of the soil

Based on the plane strain case, the dynamic equilibrium equations for the saturated soil layer can be expressed in terms of the displacement in polar coordinate system as follows [18]

$$G^*\nabla^2 u_r + (\lambda_c + G^*)\frac{\partial e}{\partial r} - \frac{G^*}{r^2}(2\frac{\partial u_\theta}{\partial \theta} + u_r) - \alpha M\frac{\partial \zeta}{\partial r} = \rho\frac{\partial^2 u_r}{\partial t^2} + \rho_f\frac{\partial^2 w_r}{\partial t^2} \tag{6a}$$

$$G^*\nabla^2 u_\theta + (\lambda_c + G^*)\frac{1}{r}\frac{\partial e}{\partial \theta} - \frac{G^*}{r^2}(u_\theta - 2\frac{\partial u_r}{\partial \theta}) - \alpha M\frac{1}{r}\frac{\partial \zeta}{\partial \theta} = \rho\frac{\partial^2 u_\theta}{\partial t^2} + \rho_f\frac{\partial^2 w_\theta}{\partial t^2} \tag{6b}$$

$$\alpha M\frac{\partial e}{\partial r} - M\frac{\partial \zeta}{\partial r} = \rho_f\frac{\partial^2 u_r}{\partial t^2} + m\frac{\partial^2 w_r}{\partial t^2} + b_p\frac{\partial w_r}{\partial t} \tag{6c}$$

$$\alpha M\frac{1}{r}\frac{\partial e}{\partial \theta} - M\frac{1}{r}\frac{\partial \zeta}{\partial \theta} = \rho_f\frac{\partial^2 u_\theta}{\partial t^2} + m\frac{\partial^2 w_\theta}{\partial t^2} + b_p\frac{\partial w_\theta}{\partial t} \tag{6d}$$

where u_r and u_θ are the displacements of solid skeleton in radial and tangential directions, respectively; w_r and w_θ are the displacements of the pore fluid relative to the solid skeleton in radial and tangential directions, respectively; λ and G^* are the complex Lame constants of the solid skeleton; α and M are the parameters accounting for compressibility of the saturated soil; $\lambda_c = \lambda + \alpha^2 M$; ρ_s, ρ_f and ρ are the mass densities of the solid skeleton, the pore fluid and the saturated soil, respectively; $\rho = \rho_s(1 - n) + n\rho_f$; $m = \rho_f/n$; n is the porosity of the saturated soil; $b_p = \rho_f g/k_d$ is viscous coupling coefficient; k_d is the