Soil Dynamics and Earthquake Engineering 112 (2018) 107–117

Contents lists available at ScienceDirect

Soil Dynamics and Earthquake Engineering

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

Vertical impedance of a pile in layered saturated viscoelastic half-space considering radial inhomogeneity

Jue Wang[a,b,*], Yufeng Gao[b]

[a] College of Mechanical & Electrical Engineering, Hohai University, Changzhou 213022, China
[b] Key Laboratory of Ministry of Education for Geomechanics and Embankment Engineering, Hohai University, Nanjing 210098, China

ARTICLE INFO

Keywords:
Soil-pile interaction
Vertical impedance
Layered saturated soil
Radial inhomogeneity
Transfer matrix

ABSTRACT

A simplified analytical approach is presented to investigated the vertical impedance of a pile embedded in layered saturated viscoelastic half-space considering radial inhomogeneity. The vertical dynamic interaction between the soil and pile is simulated by the Beam-on-Dynamic-Winkler-Foundation (BDWF) model. To characterize the variation of the soil properties in the disturbed zone around the pile, an improved complex stiffness transfer model is developed to determine the Winkler moduli based on the wave propagation theory of saturated porous medium. Vertical impedance of the pile head is obtained by solving the differential equation for axial vibration of the pile, combined with transfer-matrix formulations to deal with the layered property of the soil along the pile shaft. The validity and accuracy of the analytical solutions are demonstrated through the comparison examples for the cases of different radial variations of soil properties. Parametric studies are performed to investigate the influences of the Darcy permeability coefficient, width ratio and shear modulus ratio of the disturbed zone on the vertical impedance of the pile. It is revealed that the permeability of the pore fluid has an influence on the impedance of the pile when the Darcy permeability coefficient is large than 1×10^{-3}. In addition, the different disturbance degrees of the soil layers along the pile shaft are suggested to take into consideration in analysis of the vertical impedance of the pile embedded in layered saturated viscoelastic half-space.

1. Introduction

Vertical dynamic interaction between the soil and pile has great effects on dynamic characteristics of superstructures, such as large-scale mechanical devices, nuclear power plants or offshore structures. The substructure method is widely applied to deal with soil-structure interaction (SSI) problems as it enables each part of the system to be considered separately by its suitable method. The dynamic impedance of the pile, which describes the force-displacement relationships for interaction points at the pile head, is generally used to simulate the dynamic interaction between soil and foundation in the analysis of soil-foundation-superstructure interactions. The value of impedance is frequency-dependent and complex. The real part represents the spring which accounts for the effect of the restraining action of the supporting soil medium, whereas the imaginary part represents the dashpot which accounts for the effect of energy dissipation by radiation. Over the past few decades, numerous methods and outcomes have been proposed in literatures to analyze the dynamic impedance of piles subjected to vertical harmonic loadings [1]. With reference to simple engineering approximations, Beam-on-Dynamic-Winkler-Foundation (BDWF) model has attracted considerable research attention for obtaining dynamic impedance due to its computational efficiency. It is important to note that the reliable accuracy of the dynamic impedance of the pile strongly depends on the selection of suitable Winkler moduli.

BDWF model has a clear physical concept as the restraining action of the surrounding soil is simulated by a series of independent vertical springs K^S and dashpots C^S, which are called as Winkler moduli. Novak pioneered a plane-strain model based on two-dimensional wave propagation theory to derive the frequency-dependent expressions for Winkler moduli [2], which have been widely used in the subsequent researches [3–5]. Wang et al. [5] approximated the horizontal dynamic impedance and interaction factors for inclined piles embedded in homogeneous elastic half-space. Moreover, given the need for more accurate models of pile dynamics, Mylonakis [6] improved the plane-strain model, which accounts for the third dimension by considering the normal and shear stresses acting on the soil slice, to study the dynamic response of large-diameter end-bearing cylindrical shafts. On the other hand, simple formulations for Winkler moduli calibrated with results of

* Corresponding author at: College of Mechanical & Electrical Engineering, Hohai University, Changzhou 213022, China.
E-mail address: juewang@hhu.edu.cn (J. Wang).

https://doi.org/10.1016/j.soildyn.2018.04.036
Received 27 December 2017; Received in revised form 24 April 2018; Accepted 24 April 2018
Available online 26 May 2018
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numerical solutions are employed to investigate the impedance of axially loaded piles as a matter of experience and convenience [7–9]. Wang et al. [8,9] used the simplified formulations of Winkler moduli to analyze the horizontal harmonic vibration of vertical piles and pile group with the consideration of shear effects. Anoyatis and Mylonakis [10] improved the accuracy of the approximate analytical expressions for dynamic Winkler moduli based on linear elastodynamic theory. The aforementioned approaches for obtaining the Winkler moduli are based on the assumption that the soil medium is ideally homogeneous or horizontally layer-wise homogeneous. However, the soil around the pile is generally radially inhomogeneous due to the construction disturbances or the cyclic excitations from superstructures in practice.

To consider the inhomogeneous properties of the soil in radial direction, Novak and Sheta [11] proposed a plane-strain model which was consisted of a weakened annular inner zone around the oscillating pile and an outer zone with constant elastic properties for the rest of the medium. As the inner zone was assumed massless, this model [11] neglected the inertia effect of the inner zone which was overcame in the subsequent researches as potentially significant [12–15]. To avoid the wave reflections at the interface between two distinctly discontinuous zones with nonzero mass, the shear modulus of the inner zone was assumed to increase exponentially or parabolically in the radial direction [16,17]. Since the soil is only subdivided into two regions, these models restrict the ability to capture the radial variation of the soil properties properly. To this end, El Naggar [18,19] proposed a discrete model for radially inhomogeneous elastic half-space of single-phase. The stiffness of the composite soil layers in the disturbed zone in Refs. [18,19] was obtained by evaluating the stiffness of each annular zone separately and then joining them with a number of springs in series, which cannot reflect the dynamic interaction between adjacent annular zone. Wang et al. [20] proposed an efficient and theoretically rigorous complex stiffness transfer model in which the inner zone was further subdivided into a series annular segments along the radial direction. The vertical dynamic of a pile embedded in radially inhomogeneous half-space was further analyzed by Yang [21], Li [22,23] and their collaborators based on the above complex stiffness transfer model, as well as the torsional dynamic of piles by Wu et al. [24] and Zhang et al. [25] in recent years.

Although the radially inhomogeneous effect of the soil on the dynamic responses of piles has been studied extensively, these investigations are still limited by two following assumptions. First, the soil medium is assumed as a single-phase elastic half-space, which is not appropriate for the design of pile foundations that supported offshore structures or bridges in saturated medium. The classical Biot's theory [26–28] has been widely used to investigate the vertical dynamic response of piles embedded in radially homogeneous saturated half-space [28–30]. Liu and Wang [29] studied the effect of the permeability of saturated soils on the impedance of pile groups based on the plane-strain model. Boer [31,32] proposed a new wave propagation which further satisfied all invariance and thermodynamical conditions of soil by comparison with Biot's theory [33] and which also has been applied to the analysis of the vertical vibration of piles [34,35]. Although such researches have been performed, the investigation on the influence of radial inhomogeneity of saturated soil layer on vertical impedance of piles is still insufficient. Second, the disturbance degree of the soil in the disturbed zone, such as its width and variation of the shear modulus, is assumed to be constant along the pile shaft, while it's actually varies with the soil depth due to the soil stratification in practical engineering. The influence of varied disturbance degree of disturbed zone on the vertical dynamic impedance of a single pile has been verified by some finite element models [36,37]. Therefore, a rationally simplified analytical model, which is capable of considering the varied disturbance degree of the saturated soil along the pile shaft, would be desirable to be used in engineering applications.

As a sequel to the aforementioned studies, the present paper investigates the vertical impedance of a pile embedded in a layered saturated viscoelastic half-space considering radial inhomogeneity based on the BDWF model. The stiffness of the saturated viscoelastic and radially inhomogeneous soil in this paper is determined by a radial discrete model consisting of a series concentric annular layers based on the wave propagation theory of porous medium established by Boer [31]. The deformation and force continuity conditions at the interface of the adjacent annular layers are dealt with the transfer matrix method. The validity and accuracy of the present approach are demonstrated through the comparison examples. Parametric studies are finally undertaken to assess the influences of soil properties on the vertical impedance of the pile.

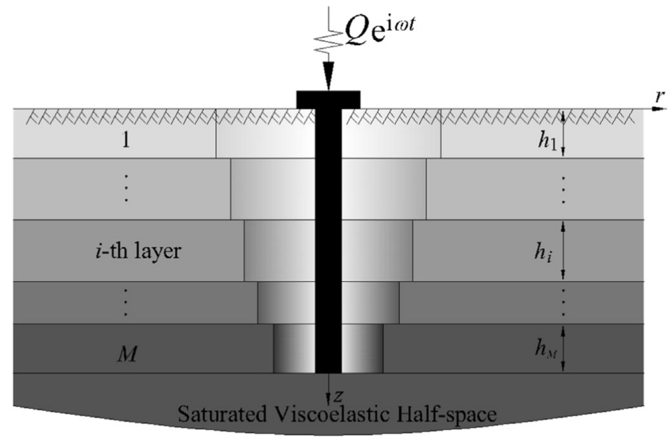

Fig. 1. A vertical dynamic pile embedded in the layered saturated viscoelastic half-space considering radial inhomogeneity.

2. Model description

Consider a cylindrical elastic pile of radius r_0 embedded in an M-layered saturated viscoelastic soil medium and excited by a vertical harmonic force $Qe^{i\omega t}$ with the frequency ω and $i = \sqrt{-1}$ on the pile head, as shown in Fig. 1. A Beam-on-Dynamic-Winkler-Foundation model is introduced to describe this soil-pile vertical dynamic interaction system, as shown in Fig. 2a. The pile-soil system is restricted in the range of small strain analysis, the pile and soil is supposed to remain in perfect contact and no sliding or cracking occurs at the pile-soil interface. According to the specific layered distribution of the soil, the pile is divided into M horizontal layers along its shaft. The vertical reaction of the soil against the pile shaft in the i-th horizontal layer with height h_i is simulated by a linear spring K_i^S and a parallel dashpot C_i^S.

To account for the radial inhomogeneity of the soil induced by construction disturbances, the saturated viscoelastic medium around the cylindrical pile is assumed to be composed by a disturbed inner boundary zone and an undisturbed outer semi-infinite zone, as shown in Fig. 2b. The disturbed inner zones of each soil layer generally have different widths Δr due to the stratification of soil property in practical engineering. For each soil layer, the complex-valued shear modulus of the soil is assumed to vary continuously according to the function $\mu^S(r)$ as follows

$$\mu^S(r) = \begin{cases} G_m(1 + i\beta_m) & r = r_0 \\ G_m(1 + i\beta_m)f(r) & r_0 < r < (r_0 + \Delta r) \\ G_0(1 + i\beta_0) & r = (r_0 + \Delta r) \end{cases} \tag{1}$$

in which

$$\mu_0^S = G_0(1 + i\beta_0) \tag{2a}$$

$$\mu_m^S = G_m(1 + i\beta_m) \tag{2b}$$

where G_m and G_0 are the shear modulus of the soil at the inner side and the outer side of the disturbed zone, β_m and β_0 are the corresponding

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