Soil Dynamics and Earthquake Engineering 90 (2016) 211–220

Contents lists available at ScienceDirect

Soil Dynamics and Earthquake Engineering

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

A study on lateral transient vibration of large diameter piles considering pile-soil interaction

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ARTICLE INFO

Article history:
Received 23 April 2016
Received in revised form
17 August 2016
Accepted 20 August 2016

Keywords:
Large diameter piles
Lateral transient vibration
Staggered grid finite difference method
Higdon absorbing boundary
Dynamic stiffness and damping ;three-dimensional interference

ABSTRACT

This study focuses on the three-dimensional (3-D) characteristics of lateral transient vibration of large diameter piles. Firstly, a 3-D pile-soil model in Cartesian coordinate system is established. Then, the governing equations are established. To eliminate the reflected waves from artificial boundaries, the second-order Higdon absorbing boundary condition is applied herein. Based on the boundary and initial conditions, the numerical solution is obtained using staggered grid finite difference method. The reliability of the numerical simulation is corroborated by comparing calculation results with measured data. It is shown that the optimal sensor location for receiving signal is the center of pile top, which is subjected to the minimum 3-D interference. Dynamic stiffness and damping at pile top are investigated by changing the parameters of pile-soil system.

1. Introduction

The pile foundation is widely used as traditional foundation form, which can bear the upper structure's load. Some piles bear large lateral loads in the project, such as the pile foundations for highrise buildings subjected to high winds and harbor construction subjected to sea wave. The lateral loads must be considered in the design of these pile foundations, which make the use of large diameter piles (≥0.8 m in diameter) more widespread and necessary. For example large diameter piles in long span bridges and offshore installations are very common and the diameter of pile is even more than two meters.

For now, according to how to properly analyze the soil around the pile, the analysis theories of laterally loaded piles boil down to: continuum theory [1–4], Winkler foundation theory [5,6], finite element theory [7,8] and boundary element method [9]. George Anoyatis et al. [4] have obtained a closed-form solution of dynamic soil reaction to a laterally-loaded pile by using 3-D continuum modeling and setting the dynamic vertical normal stresses in the soil equal to zero. Su et al. [6] have investigated the effect of lateral spreading on a single pile behind a quay wall by a Beam on Nonlinear Winkler Foundation model. These theories focus on studying soil's properties and effects on the laterally loaded piles, but the piles are merely modelled as Timoshenko beams or Bernoulli-Euler beams in these analyses, so the diameter of pile is small. In addition, the shear stress in the pile is not considered in the Bernoulli-Euler beam and the beam models are more prone to bending deformation, so they are not suitable for laterally loaded large diameter piles. Finite element (FE) analysis is a method to analyze the response of laterally loaded large diameter piles, Jeremic and Yang [7] presented a 3-D FE analysis of laterally loaded piles in soils, with soils and pile treated as elasto-plastic material and linear-elastic material, respectively. Kattis et al. [9] have studied the three-dimensional problem of isolation of vibration by a row of piles by boundary element method (BEM). However FE method focuses on analyzing the interaction of pile-soil system under lateral static or steady load, and few studies for transient vibration, whereas wind and ocean waves etc. are often transient impact to the pile foundation and the piles for isolation of vibration are sometimes subjected to transient impact force in the actual project. Besides, there is bigger gap between FE simulation and reality. Wave propagation in laterally loaded large diameter piles is not unambiguous in previous analyses. Therefore,

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Abbreviations: 3-D, three-dimensional; SGFD, staggered grid finite difference; FE, finite element; 1-D, one-dimensional

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http://dx.doi.org/10.1016/j.soildyn.2016.08.029
0267-7261/

some other methods are necessary to analyze this problem.

Lu [10] applied the staggered grid finite difference (SGFD) method to transient longitudinal vibration of piles. The velocity and stress are respectively set in two sets of interleaved sampling grid and the same process is done in time and space in the SGFD method, which makes the simulation results more accurate. The SGFD method is applied to lateral transient vibration of large diameter piles in this paper.

Lateral transient vibration in large diameter piles is complex and the stress waves will repeatedly reflect on the interface of the pile-soil. The pile-soil interaction will have an effect on the effective signal, so the 3-D effects are prominent, which can not be displayed in the one-dimensional (1-D) beam model [11]. The point of minimum 3-D interference at pile top is only studied in the longitudinal transient vibration [10] and not yet studied in the lateral transient vibration of the pile, this paper makes up for this vacancy.

About the vibration of laterally loaded piles, Yao [12] have studied the effects of shear wave velocity ratio of pile-soil and pile length on the dynamic stiffness of pile top, and Liu [13] have studied the effects of contact time of impact on the dynamic response of piles, where the piles are modelled as beams. How shear wave velocity of the soil and Young's modulus of the pile affect the dynamic response of large diameter piles are investigated in this paper .

This study presents the 3-D curve of laterally loaded large diameter pile by the SGFD method, which is closer to the measured curve by comparing with 1-D curve of Timoshenko beam model [11]. By using Higdon absorbing boundary, the SGFD method avoid the magnitude of surrounding soil thickness is ten times of pile diameter like the FE method [14] and computing area is greatly reduced. The 3-D curves show the position at the pile center is the point of minimum 3-D interference. In addition, wave propagation in the pile is clearly understood by the wave field snapshot.

2. The 3-D pile-soil model and elastic wave equations

2.1. The 3-D pile-soil model

The pile-soil model is established as shown in Fig. 1 and the pile top is subjected to lateral transient impact. The pile has a length of L, a radius of R, $P(t)$ is lateral impact force, ρ_p, λ_p and μ_p is pile's density and the Lame constants. ρ_s, λ_s and μ_s is density and the Lame constants of surrounding soil. ρ_b, λ_b and μ_b is density and the Lame constants of the soil underneath pile toe.

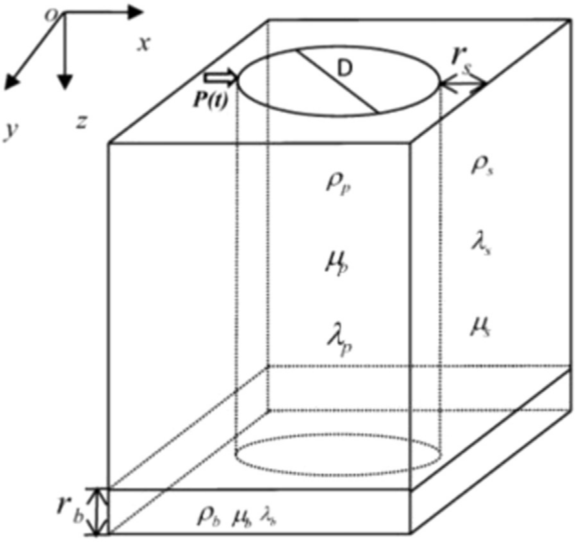

Fig. 1. 3-D model of pile-soil system.

2.2. 3-D elastic wave equations

Based on elastic theory, three-dimensional elastic wave equations are given as bellows:

$$\rho\frac{\partial v_x}{\partial t}=\frac{\partial \sigma_x}{\partial x}+\frac{\partial \tau_{xy}}{\partial y}+\frac{\partial \tau_{xz}}{\partial z} \tag{1}$$

$$\rho\frac{\partial v_y}{\partial t}=\frac{\partial \tau_{xy}}{\partial x}+\frac{\partial \sigma_y}{\partial y}+\frac{\partial \tau_{yz}}{\partial z} \tag{2}$$

$$\rho\frac{\partial v_z}{\partial t}=\frac{\partial \tau_{xz}}{\partial x}+\frac{\partial \tau_{yz}}{\partial y}+\frac{\partial \sigma_z}{\partial z} \tag{3}$$

$$\frac{\partial \sigma_x}{\partial t}=\lambda\left(\frac{\partial v_y}{\partial y}+\frac{\partial v_z}{\partial z}\right)+(\lambda+2\mu)\frac{\partial v_x}{\partial x} \tag{4}$$

$$\frac{\partial \sigma_y}{\partial t}=\lambda\left(\frac{\partial v_x}{\partial x}+\frac{\partial v_z}{\partial z}\right)+(\lambda+2\mu)\frac{\partial v_y}{\partial y} \tag{5}$$

$$\frac{\partial \sigma_z}{\partial t}=\lambda\left(\frac{\partial v_x}{\partial x}+\frac{\partial v_y}{\partial y}\right)+(\lambda+2\mu)\frac{\partial v_z}{\partial z} \tag{6}$$

$$\frac{\partial \tau_{xy}}{\partial t}=\mu\left(\frac{\partial v_x}{\partial y}+\frac{\partial v_y}{\partial x}\right) \tag{7}$$

$$\frac{\partial \tau_{xz}}{\partial t}=\mu\left(\frac{\partial v_x}{\partial z}+\frac{\partial v_z}{\partial x}\right) \tag{8}$$

$$\frac{\partial \tau_{yz}}{\partial t}=\mu\left(\frac{\partial v_y}{\partial z}+\frac{\partial v_z}{\partial y}\right) \tag{9}$$

where velocity vector $\nu=\left(v_x, v_y, v_z\right)^T$ and stress vector $\tau=\left(\sigma_x, \sigma_y, \sigma_z, \tau_{xy}, \tau_{xz}, \tau_{yz}\right)^T$, ρ is pile's density and λ, μ are pile's Lame constants

2.3. Initial conditions

At the initial moment, the pile-soil system is in static state, so velocity vector and stress vector are zero.

2.4. Boundary conditions

2.4.1. Boundary conditions of the pile side

When the pile side is subjected to the lateral impact force $P(t)$, the boundary conditions are as follows:

$$\begin{cases}\sigma_x=\begin{cases}-P(t)/\pi r_0^2, & (z-r_0)^2+y^2\le r_0^2\\ 0, & \text{others}\end{cases}\\ \tau_{xz}=\tau_{yz}=0\end{cases} \tag{10}$$