Soil Dynamics and Earthquake Engineering 67 (2014) 345–352

Contents lists available at ScienceDirect

Soil Dynamics and Earthquake Engineering

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

A study on low strain integrity testing of platform-pile system using staggered grid finite difference method

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ARTICLE INFO

Article history:
Received 27 December 2013
Received in revised form
9 October 2014
Accepted 11 October 2014

Keywords:
Platform-pile system
Low strain integrity testing
Staggered grid
Finite difference method
Three-dimensional characteristics

ABSTRACT

To study the three-dimensional characteristics of wave propagation in platform-pile system, a three-dimensional computation model for transient vibration of platform-pile-soil system is established. Based on initial and boundary conditions, the numerical solution of this model is obtained. A MATLAB program is compiled through using staggered grid finite difference method. The dynamic response of the integrate pile in platform-pile-soil system is got under vertical impact force, and the reliability and feasibility of the numerical simulation are corroborated by comparing calculation result with measured data of low strain integrity testing of platform-pile system. The optimal sensor location at platform top is studied. The results show the position distancing the pile center $0.5R \sim 0.6R$ (R is pile radius) is the optimal sensor location, which the line between sensor location and pile center parallels the short side. It plays a certain role in reducing three-dimensional interference through increasing shear wave velocity of surrounding soil and appropriately increasing the ratio of characteristic wavelength to pile radius. In addition, contact area has less influence on low strain integrity testing of platform-pile system.

1. Introduction

Low strain testing has been widely used in the integrity testing of piles, and it is based on the one-dimensional elastic rod longitudinal wave theory [1–3]. However, piles used in some projects are usually connected with a platform. So when low strain testing is used in the integrity testing of platform-pile, it is different from the testing of the single pile. When the platform-pile system is subjected to a transient loading at the top surface, spherical waves and Rayleigh waves radiate from the source. In addition to this, the stress waves will repeatedly reflect at the boundary of the platform [4]. Both surrounding piles and the pile-soil interaction will have an impact on the effective signal, and three-dimensional effects are prominent, which induce the testing signals to become more complex. Therefore, establishing three-dimensional platform-pile model and using three-dimensional wave theory have a very important significance in guiding the low-strain testing of platform-pile system.

Currently, some researchers have adopted numerical method to simulate stress waves propagation and a certain result has been obtained. Zhao et al. [5] had a preliminary discussion on various factors which impacted the stress waves in the pile with the three-dimensional explicit finite element method. Chai et al. tested the pile of platform-pile system [6,7]. At the same time, they applied the finite element method in simulating the stress propagation in the platform-pile system, and analyzed the factors that affect the effective signals in the system [7,8]. However, the model of platform-pile system is very small and the effects of soil on wave propagation are not considered. Li studied the platform-single pile system with the low strain testing [9]. However, currently, most of the researches are focused on the pile, with fewer studies on the platform-pile system. Besides, the accuracy was low by the finite element method simulation, and the results require complex filtration. Eventually leading to some important signals would be filtered out at the same time. Therefore, some other methods are necessary to analyze and study wave propagation in platform-pile system.

Liu [10] and Long [11] et al. introduced the difference method to the study of the low-strain testing of piles, and achieved better results. Ke [12], Duan [13] and Lu [14] et al. applied the staggered grid finite difference method to the three-dimensional testing of piles and obtained higher accurate results. The staggered grid finite difference method is a very stable, efficient and powerful numerical method to simulate elastic wave propagation in various media and is also widely used in other areas [15–20].

The purpose of this article is to study the wave propagation in platform-pile system by using staggered grid finite difference method. Firstly, a computational model of platform-pile system in Cartesian

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http://dx.doi.org/10.1016/j.soildyn.2014.10.009
0267-7261/

coordinate system is established under low strain integrity testing conditions. The numerical solution is obtained on the basis of boundary and initial conditions. Then, the reliability and feasibility of the numerical simulation is verified by comparing with measured data. At last, the vertical velocity curves at platform top are got, and the optimal sensor location is also obtained. In addition to this, the effects of size of platform, contact area and characteristic wavelength of impact force, surrounding soil on testing results are also respectively discussed in order to induce three-dimensional interference.

2. Computational model and basic equations

2.1. Computational model

Fig. 1 shows the computational model of platform-pile system was embedded in soil mass, which has two piles. The platform has a length of l, a width of w, and a thickness of h. The pile has a length of L, a radius of R. d is pile spacing. ρ_p, λ_p and G_p are the density and Lame constants of platform-pile system. ρ_s, λ_s and G_s are the density and Lame constants of surrounding soil. ρ_b, λ_b and G_b are the density and Lame constants of soil underneath pile tip. The platform top to which the pile center corresponds was subjected to a vertical impact force $p(t)$.

2.2. Three-dimensional elastic wave equations

Platform-pile system and soil are set as linear elastic materials under low strain integrity testing conditions. The body forces are not taken into account in platform-pile-soil system, and pile maintains close contact with soil. Based on elastic theory, three-dimensional elastic wave equations are given as bellows:

$$\rho\frac{\partial \mathbf{v}}{\partial t}=\mathbf{A}\frac{\partial \boldsymbol{\tau}}{\partial x}+\mathbf{B}\frac{\partial \boldsymbol{\tau}}{\partial y}+\mathbf{C}\frac{\partial \boldsymbol{\tau}}{\partial z}, \tag{1}$$

$$\frac{\partial \boldsymbol{\tau}}{\partial t}=\mathbf{H}\left(\mathbf{A}^{\mathrm{T}}\frac{\partial \mathbf{v}}{\partial x}+\mathbf{B}^{\mathrm{T}}\frac{\partial \mathbf{v}}{\partial y}+\mathbf{C}^{\mathrm{T}}\frac{\partial \mathbf{v}}{\partial z}\right). \tag{2}$$

where ρ, λ and G are the density and Lame constants of elastomer, velocity vector $\mathbf{v}=(v_x, v_y, v_z)^{\mathrm{T}}$and stress vector$\boldsymbol{\tau}=(\tau_{xx}, \tau_{yy}, \tau_{zz}, \tau_{xy}, \tau_{yz}, \tau_{zx})^{\mathrm{T}}$, matrices $\mathbf{A}$,$\mathbf{B}$,$\mathbf{C}$ and $\mathbf{H}$ are the following:

$$\mathbf{A}=\begin{pmatrix}1&0&0&0&0&0\\0&0&0&1&0&0\\0&0&0&0&0&1\end{pmatrix}, \mathbf{B}=\begin{pmatrix}0&0&0&1&0&0\\0&1&0&0&0&0\\0&0&0&0&1&0\end{pmatrix},$$

$$\mathbf{C}=\begin{pmatrix}0&0&0&0&0&1\\0&0&0&0&1&0\\0&0&1&0&0&0\end{pmatrix},$$

$$\mathbf{H}=\begin{pmatrix}\lambda+2G&\lambda&\lambda&&&\\\lambda&\lambda+2G&\lambda&&\mathbf{0}&\\\lambda&\lambda&\lambda+2G&&&\\&&&G&0&0\\&\mathbf{0}&&0&G&0\\&&&0&0&G\end{pmatrix}.$$

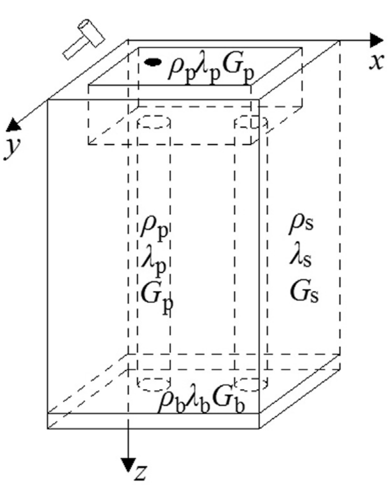

Fig. 1. Three-dimensional computational model of platform-pile-soil system.

2.3. Initial conditions

Platform-pile-soil system is in quiescence before the vertical impact force $p(t)$ is applied, so the initial conditions for system are set as: $\begin{cases}\mathbf{v}|_{t=0}=\mathbf{0},\\ \boldsymbol{\tau}|_{t=0}=\mathbf{0}.\end{cases}$

2.4. Boundary conditions

2.4.1. Boundary conditions of the top surface

When the top surface of the platform is subjected to a vertical impact force $p(t)$, the boundary conditions are restricted by:

$$\tau_{zz}(x,y,z,t)|_{z=0}=\begin{cases}-p(t)/(\pi r_0^2), & x^2+y^2\le r_0^2;\\ 0, & \text{others}\end{cases} \tag{3}$$

$$\tau_{xz}(x,y,z,t)|_{z=0}=\tau_{yz}(x,y,z,t)|_{z=0}=0. \tag{4}$$

in which,

$$p(t)=\begin{cases}\frac{I_p}{t_0}\left(1-\cos\frac{2\pi}{t_0}t\right), & (0\le t\le t_0);\\ 0, & (t\ge t_0)\end{cases} \tag{5}$$

where I_p, t_0 and r_0 are the impulse, contact time and contact radius of impact force.

2.4.2. Continuity conditions

On the interface between platform-pile system and soil, i.e., on the platform-pile system outside surface, one should claim continuity of the velocity vector $\mathbf{v}$ and the vector of normal stresses $\boldsymbol{\sigma}=(\tau_{xx}, \tau_{yy}, \tau_{zz})^{\mathrm{T}}$.

2.4.3. Absorbing boundary conditions

Since the platform-pile-soil system is semi-infinite in practice, if the computational domain is very large, it cannot be simulated by computer. Therefore, artificial boundary should be created. However, if the artificial boundary is created, the energy will reflect on artificial boundary. In order to make the energy transmitted to the outside on the artificial boundary without generating reflections, second-order Higdon absorbing boundary condition [21,22] is adopted herein.

$$\left(\prod_{j=1}^{2}\left(\cos\,\alpha_j\frac{\partial}{\partial t}-c\frac{\partial}{\partial x}\right)\right)u=0. \tag{6}$$

where α_j is angle of incidence, c is the propagation velocity of incident wave. When the angle of incidence is $\pm\,\alpha_j$, Formulation(6) is satisfied exactly, and there is perfect absorption.

3. Discrete equations

In this article, staggered grid finite difference method is adopted. The velocity components and stress components are defined in two different sets of grid. Staggered grid is used not only in space but also in time.