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Numerical study of pile group effect on wave-induced seabed response

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ABSTRACT

Wave-induced seabed response around pile foundations affects the seabed stability, thereby threatening the structure safety, and numerous studies have been performed to explore the wave-structure-seabed interaction (WSSI) around mono-pile. However, little attention has been paid to WSSI around pile groups. In the present study, based on an integrated model, WSSI around three-pile group is numerically examined, and the effects of wave obliquity, pile diameter, pile spacing and embedment depth are parametrically explored. In this model, Reynolds-Averaged Navier-Stokes (RANS) equations with k-ε turbulence model and Biot's quasi-static (QS) model for poro-elastic medium are adopted to govern the wave motion and seabed response, respectively. The results reveal that the effects of wave obliquity and pile diameter are significant, whereas the influences of pile spacing and embedment depth are negligible.

1. Introduction

Pile foundations are widely applied in coastal engineering practice (e.g., offshore wind turbines [1–3], sea bridges [4] and petroleum platforms [5]). Unlike the inland ones, offshore pile foundations are more vulnerable due to various oceanic loads [6], among which wave loading may generate excessive pore water pressure in seabed, leading to seabed liquefaction or shear failure [7], and thereby affecting the structure safety.

There are two mechanisms of wave-induced pore pressure in seabed, i.e. the oscillatory mechanism [8,9] and residual mechanism [10,11]. In most cases, the wave-induced seabed response is oscillatory, except for some special cases of non-cohesive sediments with loose to medium density [12,13]. For the wave-induced oscillatory seabed response, numerous numerical models were established based on the framework of Biot's theories for poro-elastic medium [14–16], including the quasi-static (QS) model, partly dynamic (PD) model and fully dynamic (FD) model. In QS model, the inertia terms of fluid and soil particles are both ignored, while only that of fluid is neglected in PD model. To identify the applicabilities of these three models, Ulker et al. [17] developed a set of analytical solutions to free seabed response under plane strain condition. Based on their results, Sumer [18] summarized that for low permeability soil (permeability $k_s = 1 \times 10^{-5}$ m/s), no inertia effect exists, and even for a large permeability soil ($k_s = 1 \times 10^{-2}$ m/s, gravel actually), the difference between the results of FD (PD) and QS model is less than 5%. Therefore, for most engineering problems, the inertia effects can be ignored as revealed by Cheng and Liu [19], and QS model could be served as a cost-effective tool in numerical simulation.

In the past decade, numerous numerical studies have been carried out to examine the wave-induced oscillatory seabed response around mono-pile foundations. Based on boundary element method, Lu and Jeng [20] developed a coupled model to study the linear wave-induced seabed response and mono-pile deformation with seawater described by Helmholtz equation. Li et al. [21] proposed a three-dimensional (3D) seabed-pile coupled model using finite element method (FEM) to simulate the wave-induced oscillatory and residual pore pressure response, wherein analytical wave pressure is applied on seabed surface with Stokes wave theory, and effects of soil permeability and pile diameter are parametrically studied. Sui et al. [22] developed another one-way coupled model to simulate the dynamic oscillatory seabed response with wave motion described by nonlinear Boussinesq equations, and found that maximum pile displacement is less than 4×10^{-6} times the pile radius. Zhang et al. [23] carried out 3D one-way coupling studies to examine the effect of mono-pile on wave-induced oscillatory seabed response. In their model, RANS equations solved by finite volume method are adopted to govern wave motion and it is revealed that existence of mono-pile foundation would decrease the seabed response around mono-pile. Then, based on fully dynamic Biot's equations and linear wave theory, Zhang et al. [24] studied the non-homogenous seabed response around mono-pile. Recently, Lin et al. [25] developed an integrated 3D model to explore strong nonlinear wave-induced seabed response around mono-pile within the framework of OpenFOAM, and parametric study of embedded depth shows that increasing

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embedment depth significantly reduces the magnitude of pore pressure along mono-pile foundation. Then Zhao et al. [26] extended this study to enclose the residual seabed response with the formulation proposed by Sassa et al. [27].

However, exploration on wave-induced seabed response around pile-group foundation commenced relatively later, and is scarcely carried out up to date. Sui et al. [28] provided a preliminary work on the wave-induced seabed response around four-square-pile group and studied the influences of degree of saturation and permeability on seabed response. Chang and Jeng [29] further performed a case study to explore the wave-induced seabed response around high-rising structure foundation of Donghai Offshore Wind Farm, which is composed of eight inclined steel piles and a concrete cap, and it is demonstrated that replacing seabed soils around pile foundation with coarser ones offers effective protection against liquefaction. Recently, Zhang et al. [30] carried out a 3D numerical simulation to examine the wave-induced seabed response around a four-pile platform considering structure response. In this study, parametric studies were conducted to explore the effects of pile diameter and pile insertion ratio on seabed and structure response.

It is well known that pile group may have numerous configurations, and pile group effect on wave-induced seabed response is a primary concern, which involves the pile diameter, pile spacing, embedment depth, wave obliquity, etc. For purpose of optimizing pile group configuration, it is vital to explore the effects of these factors on seabed response.

Due to the diversity of pile group formation, it is unrealistic to carry out study for each configuration, and it is expedient to study several typical configurations, among which three-pile group is the simplest and a common type of pile group in offshore practice [2,31,32]. Numerous studies have been performed to investigate the nearby local scour development [33–35] and the wave force acting on three-pile groups and the superstructures [36–38]. However, little attention has been paid to the wave-induced seabed response around three-pile group.

In the present study, parametric study around three-pile groups will be numerically conducted to explore the pile group effect on wave-induced seabed response with regard to wave obliquity, pile diameter, pile spacing and embedment depth. RANS equations with $k-\varepsilon$ turbulence closure are employed to describe the wave-induced fluid motion. Following the instructions of Sumer [18] as aforementioned, Biot's QS theory is adopted to capture the seabed response. The wave and seabed modules are solved by finite difference method (FDM) and FEM, respectively.

2. Numerical model

The present numerical model is composed of wave and seabed submodels, which are governed by RANS equations and QS Biot's equations for poro-elastic medium [14], respectively. In the previous studies, both sets of governing equations have been adopted in the examination of wave-induced seabed response around pile foundations [25,26,29], breakwaters [39], and pipelines [40,41]. The integration method of the sub-models will be also demonstrated in this section. Fig. 1 illustrates the definition of WSSI in the vicinity of three-pile group. Ye and Jeng [42] suggested that the seabed model length should be at least two times the incident wavelength to diminish the effect of fixed boundaries in case of free seabed under wave and current combined loading. In the present model, the model size is set as $4L_w \times 2L_w$, where L_w is the incident wavelength. The origin of Cartesian coordinates, O, is located at the center of the pile group on the seabed surface. The wave incident angle, θ, ranges from 30° to 90°.

2.1. Wave sub-model

For incompressible fluid motion, mass and momentum conservations are shown as follows, respectively:

$$\frac{\partial u_{fi}}{\partial x_{fi}} = 0 \tag{1}$$

$$\frac{\partial \rho_f u_{fi}}{\partial t} + \frac{\partial \rho_f u_{fi} u_{fj}}{\partial x_j} = -\frac{\partial p_f}{\partial x_i} + \frac{\partial}{\partial x_j}\left[\mu\left(\frac{\partial u_{fi}}{\partial x_j} + \frac{\partial u_{fj}}{\partial x_i}\right)\right] + \frac{\partial}{\partial x_j}(-\rho_f u_{fi}' u_{fj}') + \rho_f g_i \tag{2}$$

where $u_{fi}(i = 1, 2, 3)$ is the ensemble mean fluid velocity in x, y and z-direction, respectively; u_{fi}' is the fluctuating velocity; p_f is the fluid pressure; μ is the dynamic viscous; $x_{fi}(i = 1, 2, 3)$ are the coordinates x, y and z, respectively; ρ_f is the fluid density; t is the time and $g_i(i = 1, 2, 3)$ are the body forces in x-, y- and z-direction, respectively. In the present study, the only body force is gravity, $g = 9.80665\,\mathrm{m/s^2}$.

The term $-\rho_f u_{fi}' u_{fj}'$ in Eq. (2) is the so-called Reynolds stress, which can be estimated by eddy viscosity model:

$$-\rho_f u_{fi}' u_{fj}' = \mu_t\left[\frac{\partial u_{fi}}{\partial x_j} + \frac{\partial u_{fj}}{\partial x_i}\right] - \frac{2}{3}\left(\rho_f k + \mu_t \frac{\partial u_i}{\partial x_i}\right)\delta_{ij} \tag{3}$$

where μ_t is the turbulent viscosity, $k = \frac{1}{2}u_{fi}' u_{fi}'$ is the turbulent kinematic energy and δ_{ij} is the Kronecker delta:

$$\delta_{ij} = \begin{cases} 1, & i = j \\ 0, & i \neq j \end{cases} \tag{4}$$

By substituting Eq. (3) into Eq. (2), Eq. (2) could be expressed by

$$\frac{\partial \rho_f u_{fi}}{\partial t} + \frac{\partial \rho_f u_{fi} u_{fj}}{\partial x_j} = -\frac{\partial p_f + \frac{2}{3}\rho_f k}{\partial x_i} + \frac{\partial}{\partial x_j}\left[\mu_{eff}\left(\frac{\partial u_{fi}}{\partial x_j} + \frac{\partial u_{fj}}{\partial x_i}\right)\right] + \rho_f g_i - \frac{2}{3}\mu_t \frac{\partial}{\partial x_j}\left[\frac{\partial u_i}{\partial x_i}\delta_{ij}\right] \tag{5}$$

where $\mu_{eff} = \mu + \mu_t$ is the total effective viscosity.

In order to solve Eqs. (1) and (5), $k-\varepsilon$ turbulence model [43] is adopted. Firstly, a variable called turbulent dissipation rate is introduced into the model:

$$\varepsilon = \frac{\mu}{\rho_f}\overline{\left(\frac{\partial u_{fi}'}{\partial x_k}\right)\left(\frac{\partial u_{fi}'}{\partial x_k}\right)} \tag{6}$$

Hence a connection between ε and turbulent kinematic energy k could be established as

$$\varepsilon = C_D \frac{k^{\frac{2}{3}}}{l} \tag{7}$$

in which C_D is a constant, l is a length representing the macroscale of turbulence.

Eventually, the $k-\varepsilon$ turbulence model is derived as

$$\frac{\partial(\rho_f k)}{\partial t} + \frac{\partial(\rho_f k u_{fi})}{\partial x_i} = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right] + G_k - \rho_f \varepsilon \tag{8}$$

$$\frac{\partial(\rho_f \varepsilon)}{\partial t} + \frac{\partial(\rho_f \varepsilon u_{fi})}{\partial x_i} = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_j}\right] + \frac{C_{1\varepsilon}}{k}G_k - C_{2\varepsilon}\rho_f \frac{\varepsilon^2}{k} \tag{9}$$

$$\mu_t = \frac{C_\mu \rho_f k^2}{\varepsilon} \tag{10}$$

$$G_k = \mu_t\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)\frac{\partial u_i}{\partial x_j} \tag{11}$$

where the values of constants σ_k, σ_ε, $C_{1\varepsilon}$, $C_{2\varepsilon}$, C_μ are as follows: $\sigma_k = 1.00$, $\sigma_\varepsilon = 1.30$, $C_{1\varepsilon} = 1.44$, $C_{2\varepsilon} = 1.92$, $C_\mu = 0.09$[44].

To diminish the wave reflection from the outflow boundary, a sponge layer is adopted to absorb waves in front of the outlet boundary, in which the Navier-Stokes equation is modified as