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Numerical Study for Wave-Induced Oscillatory Seabed Response Around Pile Foundations Using OpenFOAM

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In this paper, a three-dimensional numerical model for wave–seabed interactions around a group of pile foundations is proposed. Unlike in previous studies, both wave and seabed submodels are developed based on the open source library OpenFOAM (version 4.0, foundation). In this model, the wave motion is governed by RANS equations, while the porous flow in the seabed is governed by dynamic poro-elastic $u-p$ approximation. The present model is first validated with the previous laboratory experiments for a single pile. Then, the present model is further applied to the cases of group of pile foundations. Numerical results indicate that the wave characteristics as well as the configurations of the structures can significantly affect the oscillatory pore water pressures and vertical effective normal stresses around a group of pile foundations.

INTRODUCTION

Pile foundations are commonly used to support various offshore infrastructures such as platforms in shallow water, cross-sea bridge piers, offshore wind turbine foundations, etc. For the design of a pile foundation, seabed stability (including soil liquefaction, scour, and shear failure) in the vicinity of the structure needs to be taken into consideration. Furthermore, wave-induced pore water pressures and effective stresses are two key factors for the estimation of wave-induced seabed instability. With an increase of pore water pressures and a decrease of vertical effective normal stresses due to wave loading, part of the seabed may become unstable or even liquefied. Once the liquefaction occurs, the liquefied soil will behave like a heavy fluid and can only provide very little resistance to the pile foundations.

Two mechanisms of the wave-induced soil response have been observed in previous laboratory experiments and field measurements (Zen and Yamazaki, 1990), depending on the manner in which the pore water pressure is generated. They are residual and oscillatory mechanisms. Among these, the residual mechanism is caused by the progressive nature of the excess pore water pressure, which usually appears at the initial stage of cyclic loading (Seed and Rahman, 1978; Sumer and Fredsøe, 2002). The oscillatory mechanism is normally accompanied by amplitude damping and phase lag to the pore water pressures (Yamamoto et al., 1978; Jeng, 2013). This type of soil response usually occurs periodically during a storm event. In this study, we focus only on the oscillatory soil dynamic response.

Numerous studies of the wave-induced oscillatory soil response based on Biot's poro-elastic theory (Biot, 1941) have been carried out since the 1970s (Yamamoto et al., 1978). Most previous studies of wave–seabed–structure interaction (WSSI) systems considered either breakwaters or pipelines (Cheng and Liu, 1986; Jeng et al., 2013). Only a few studies considered the pile foundations. For example, Li et al. (2011) numerically studied the wave-induced pore water pressures in a porous seabed based on a 3-D finite element method (FEM) model. In their study, only small-diameter piles are considered. Therefore, wave diffraction due to the existence of a pile foundation was excluded. Later, Chang and Jeng (2014) examined the oscillatory soil dynamic response around the offshore wind turbine foundation using an integrated numerical model in which the inclined piles were considered. Qi and Gao (2014) investigated the wave/current-induced pore water pressures and the local scour around the monopile foundation based on the laboratory experiments, and they found a relationship between the pore water pressures and scour depth under wave and current loadings. Recently, Lin et al. (2017) examined the nonlinear wave-induced oscillatory soil dynamic response in the vicinity of a monopile foundation by an integrated numerical model for wave–seabed interaction around structures, in which the inertial effects of the soil skeleton were ignored. Furthermore, preconsolidation due to the self-weight of the structure, which has proved to directly affect the initial stresses around the structure (Jeng et al., 2013), was not considered in their model. Therefore, the predicted liquefaction potential presented by Lin et al. (2017) was incorrect. Zhang et al. (2017) studied the transient soil response around a four-pile foundation due to wave loading, in which the flow motions were simulated based on the FDM code (FLOW-3D), and the seabed model was built using the FEM code (COMSOL Multiphysics). Zhao et al. (2017) further considered the wave-induced oscillatory and residual soil liquefaction around a monopile by integrating the FLOW-3D and COMSOL seabed model. Note that the aforementioned studies considered only quasi-static soil behavior and ignored the inertial effects.

This study is aimed at developing a one-way coupled model (PORO–FSSI–FOAM) for the wave-induced seabed response around pile foundations using OpenFOAM. IHFOAM is used to simulate the flow motions around the structure, and Seabed–FOAM is established to simulate the soil dynamic response within the seabed, based on $u-p$ approximation. Validations of the

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