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Three-dimensional modeling of wave-structure-seabed interaction around twin-pile group

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ABSTRACT

In this paper, a preliminary study of wave-induced oscillatory seabed response around twin-pile group is performed using a three-dimensional (3D) model, and meanwhile comparative analysis with mono-pile is conducted. In the proposed model, Reynolds-Averaged Navier-Stokes (RANS) equations with $k-\varepsilon$ turbulence model is applied to simulate the wave motion, while Biot's poro-elastic theory for the porous seabed is employed to govern the seabed response. Validation against available experiment data and analytical solution demonstrates that the present model has the capacity of simulating wave-structure-seabed interaction (WSSI) around pile structures. Results show that magnitudes of wave-induced oscillatory pore pressure and liquefaction depth around twin-pile group tend to attenuate along the pile-pile centerline, presenting significant difference from that around mono-pile.

1. Introduction

There are various oceanic dynamic loadings such as wave, current and earthquake that ocean engineers might encounter in design of offshore structures (Wisch, 1998; Zhang et al., 2010; Ye and Wang, 2015). Among these, water wave attracts great concern. When wave train propagates above seabed, significant dynamic pressure is generated and transferred into the seabed, inducing variation of pore water pressures and stresses within the seabed (Madsen, 1978). Under the wave trough, the pore pressure is negative and generates suction force on seabed soil. When it diminishes the gravitational resistance of soil particles, the seabed soil would be liquefied. Once liquefaction occurs, the soil fabric is broken down by the pore fluid (Sumer, 2014), and the soil particles are likely to be carried away by the seawater flow, thus could further lead to scour (Sumer and Fredsøe, 2001). Wave-induced shear failure and liquefaction have been identified as two of the main reasons that lead to the damage of marine structures (Sterling and Strohbeck, 1975; Bea et al., 1983; Silvester and Hsu, 1989).

In general, two mechanisms of the wave-induced pore pressure response have been reported in the literature (Zen and Yamazaki, 1990; Nago et al., 1993; Sassa and Sekiguchi, 1999). They are oscillatory pore pressure and residual pore pressure. Oscillatory pore pressure is directly generated by the momentary wave pressure and accompanied by the damping of amplitude and phase lag, and appears as periodic response to water waves. However, residual pore pressure is induced by the plastic soil behavior. In most marine sediments, wave-induced soil response is oscillatory in nature, except for those induced by some extreme loads such as tsunami or storms (Seed and Rahman, 1978). Thereby, oscillatory seabed response is the major concern when estimating seabed response around offshore installations in normal ocean conditions without plastic seabed deformation. In this study, we only consider the oscillatory soil response. For more detailed information regarding the applicability of these two mechanisms, the readers can refer to Jeng and Seymour (2007).

Wave-induced seabed response around offshore pile foundations is crucial in evaluating structure instability. Recently, some research works have been carried out to explore wave-induced seabed response around pile foundations. Li et al. (2011) adopted a 3D model using finite element method (FEM) to explore wave-induced pore pressure response and liquefaction around a mono-pile in seabed. The wave load applied is from the analytical solution that does not consider wave-pile interaction. Sui et al. (2015) conducted a 3D research on seabed and mono-pile response.

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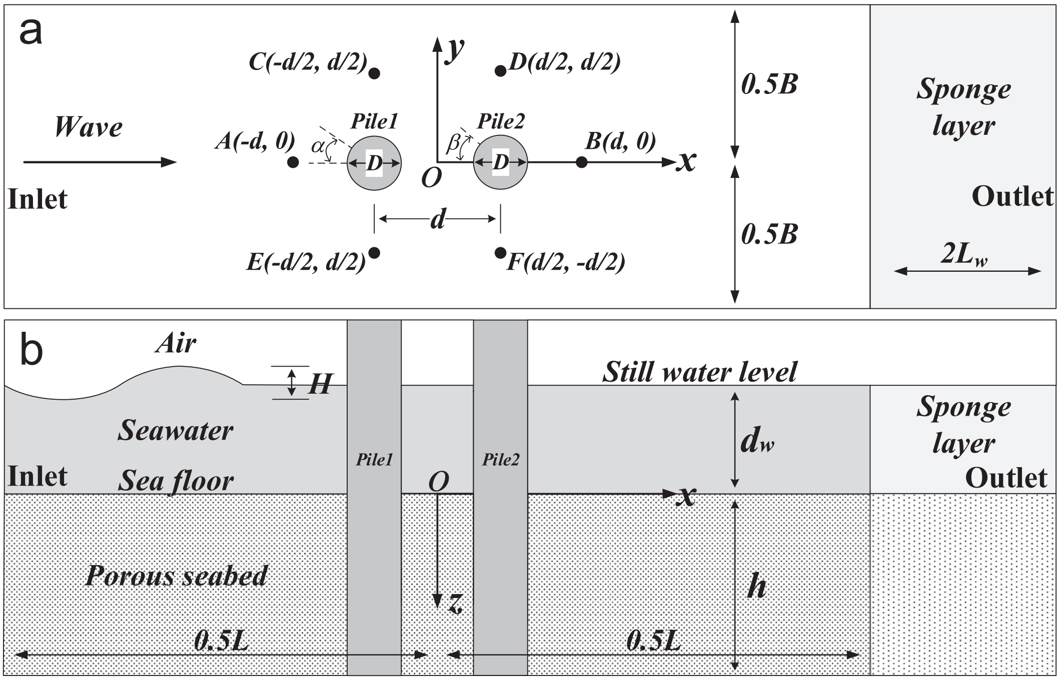

Fig. 1. Sketch of numerical model. (a) Plane view, (b) Section view.

The results show that the maximum pile displacement is less than 4×10^{-6} times the pile radius, which implies that effect of pile displacement on wave propagation could be ignored under common wave conditions with small wave amplitude. Recently, Lin et al. (2017) developed an integrated 3D numerical model using OpenFOAM and thoroughly explored the nonlinear wave-induced seabed response and liquefaction around mono-pile considering various embedment depths.

As a matter of fact, except for those used as the foundation of wind turbines (Negro et al., 2017), offshore pile foundations are usually working in the form of pile group with pile-group effect, which means one pile may significantly influence the performance of other piles and meanwhile the fluid motion and seabed response will be totally different from those of mono-pile. Hence, seabed response under wave-seabed-pile group interaction needs to be taken into consideration in the estimation of the marine structure instability. Chang and Jeng (2014) developed a 3D model to investigate the wave-induced seabed response around a pile-supported foundation of offshore wind turbine, and discussed the effects of wave height, wave period, seabed permeability, and degree of saturation on soil response. However, the pile group of the turbine is complex with eight vertically inclined piles, thus the study lacks of universality as pile foundations are normally upright (Randolph, 2003). Zhang et al. (2017) further studied the wave-induced seabed response around a four-pile platform with thorough parametric studies, however omitting to examine the wave-induced liquefaction. Therefore, study for seabed response around pile group is still in need to enhance the understanding of WSSI regarding pile-group effect and liquefaction.

When examining seabed response around pile structures, the interaction between seawater and pile is supposed to be taken into account. When a mono-pile or pile group is placed in the wave field, the flow regime changes. The vortices behind the pile arise immediately and shed consecutively due to the inherent viscosity of water (Williamson, 1996). Hence, appropriate turbulence model should be adopted in numerical simulation of fluid field around pile structures. In the past several decades, wave-induced turbulent flow (Sarpkaya, 2004) around mono-pile or so-called cylinder and corresponding seabed response have been widely studied, whereas academic exploration of wave-pile group-seabed response is still scarce as mentioned above.

Twin piles are the simplest form of pile group, and can be used to explore the influence of one pile on the flow field around other piles when subjected to wave loading. Thus, twin piles could be served as a research object in simulation of WSSI around pile group foundations.

There have been several studies that examined the wave or current induced scour around twin piles. To the author's knowledge, study on wave-induced process around twin-piles should be initiated by Sumer and Fredsøe (1998) with experimentation. In their experiments, the wave-induced scour around twin piles, three piles and 4×4 piles is comprehensively tested, and it was revealed that the scour around a pile group is different from that around a mono-pile. Liang et al. (2013) further experimentally explored the local scour around twin piles under oscillatory flows. Recently, Li et al. (2016) carried out flume tests to examine local scour around twin piles under combined wave and current loading in submarine environment. Despite above studies on scour around twin piles, the wave-induced seabed response around twin piles has not been explored, therefore this paper will present an attempt to fill this gap.

This study investigates the WSSI around a twin-pile foundation using a 3D numerical scheme that could model the potential turbulence. By

Table 1
Input data of the present study.

Parameter	Description	Notation	Magnitude	Unit
Wave parameters	Wave period	T	4	s
	Wave height	H	1.2	m
	Water depth	d_w	4	m
	Wavelength	L_w	20.8615	m
Seabed parameters	Seabed thickness	h	8	m
	Seabed model length	L	83.446	m
	Seabed model width	B	41.723	m
	Permeability	k_s	10^{-5}	m/s
	Degree of saturation	S_r	0.98	–
	Porosity	n_s	0.3	–
	Poisson's ratio	ν	0.4	–
	Shear modulus	G	10^7	Pa
Pile parameters	Pile diameter	D	2	m
	Pile distance	d	4	m