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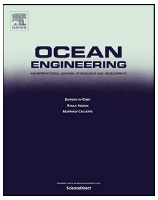

Numerical study for wave-induced oscillatory pore pressures and liquefaction around impermeable slope breakwater heads

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ABSTRACT

The problem of wave-structure-seabed interactions (WSSI) around impermeable slope breakwater head is numerically investigated with a three-dimensional (3D) integrated model. The Reynolds-averaged Navier-Stokes (RANS) equations are adopted to simulate the wave-induced fluid motion, and Biot's theory for poro-elastic medium is employed to describe the seabed behaviour under wave loading. A calculation scheme is established to integrate both wave motion and seabed response. The numerical results reveal that wave-induced flow field in the vicinity of breakwater heads is significantly disturbed by the existence of the structure, leading to wave reflection, diffraction and overtopping. Furthermore, the wave-induced negative pore pressure and liquefaction near the front of the breakwater heads is significant. The parametric study concludes that the increase of breakwater slope intensifies the seabed response and liquefaction around the breakwater head, and therefore it is proposed to design breakwaters with a mild slope.

1. Introduction

The phenomenon of the wave-structure-seabed interactions (WSSI) has attracted great concern from researchers and practical engineers in the field of ocean engineering involving the design of marine infrastructure such as pipelines (Sumer, 2014), breakwaters (Ye et al., 2013a, b, 2016, 2017) and pile foundations (Lin et al., 2017; Sui et al., 2017, Zhao et al., 2017a,b). There have been numerous reports on the wave-induced structure failure worldwide such as the Sines breakwater failure (Smith and Gordon, 1983) and offshore platform failure of Mississippi River Delta (Bea et al., 1983). The failure of Sines is directly induced by breakage of dolosse (Silvester and Hsu, 1989), while the latter is mainly caused by seabed movement. Among the reasons for marine structure failures, seabed instability plays a critical role. Under the action of wave loading, pore water pressure would be generated in the seabed. When it exceeds certain limit, seabed liquefaction and shear failure might happen, and further lead to structure failure (Oumeraci, 1994; Rahman, 1991).

Based on laboratory experiments and field studies, two mechanisms of wave-induced pore pressures have been reported in the literature, i.e. the oscillatory mechanism and residual mechanism (Zen and Yamazaki, 1990; Nago et al., 1993; Jeng, 2013). The oscillatory mechanism is the basic feature of wave-induced pore pressure, which is caused by the cycling excitation of wave trains. However, the residual mechanism is induced by the contraction of relatively loose soil (Seed and Rahman, 1978; Sassa and Sekiguchi, 1999), and mainly occurs when the seabed is enduring extreme loadings such as storm and tsunami. The importance and applicable range of both mechanisms have been reported in Jeng and Seymour (2007). In this study, we focus on the oscillatory soil response and its resultant momentary liquefaction.

Breakwater is one of the most common coastal structures, which is used to protect the coastal facilities such as a harbour from strong wave and storm loading. Hence, breakwater is susceptible to wave-induced failure, and gains lots of attention from coastal engineers and researchers. Recently, focusing on the wave-induced seabed response, many efforts are being devoted to deal with WSSI around breakwaters, including field monitoring (Dean et al., 1997; Guler et al., 2015), analytical solutions (Jeng, 1997), physical modelling (Kudella et al., 2006) and numerical simulation (Jeng et al., 2001; Mostafa et al., 1999; Ulker et al., 2010; Jeng et al., 2013; Ye et al., 2012, 2016). However, most of the studies only consider the WSSI in front of the breakwater trunk.

As a matter of fact, WSSI in vicinity of breakwater heads is different from that around breakwater trunk. Vidal et al. (1991) experimentally

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studied the stability of a slope breakwater's head and trunk, and found that the head and trunk display different behaviour when damage grows and the head section is more vulnerable than trunk section. The major reason for this difference is supposed to be that the flow regime around breakwater head is different from trunk section. When wave reaches the breakwater head, it causes steady streaming, plunging breaker, streamline contraction and lee-wake vortices, giving rise to complex effects on seabed and thus resulting in seabed destruction such as scour (Fredsøe and Sumer, 1997).

Recently, a few researchers have paid attention to WSSI in vicinity of breakwater head. Li and Jeng (2008) and Jeng and Ou (2010) numerically simulated the wave-induced seabed response around breakwater head taking into account of incident, reflected and diffracted waves. However, the breakwater used in their model is simplified as a single line without width and height, and only linear wave theory is used in their model. Zhao et al. (2013) then studied the wave-induced seabed response around a vertical breakwater head using a 3D integrated numerical model taking into account of turbulence. As a matter of fact, breakwater configuration such as shape significantly affects the wave diffraction around the breakwater head, thus determining the wave loading acting on seabed. Therefore, wave-induced seabed response varies with breakwater configuration.

In this paper, a 3D integrated numerical scheme, consisting of wave sub model and seabed sub model, is proposed to explore the seabed response around slope breakwater head. Reynolds-averaged Navier-Stokes equations (RANS) with $k-\varepsilon$ turbulent model are used to describe the wave motion. Thus, the wave-induced turbulence in the vicinity of breakwater could be appropriately modelled. Under ordinary wave loadings, the quasi-static (QS) equations proposed by Biot (1941) is sufficient and efficient for modelling seabed response (Ulker et al., 2009), and is adopted to model the seabed response in the present study. The realization of the proposed numerical scheme is performed using OpenFOAM and COMSOL scripts (COMSOL with MATLAB). Firstly, in wave sub-model, the RANS equations with $k-\varepsilon$ turbulence closure in OpenFOAM is employed to calculate the wave pressure in the first two wave periods. In the present study, we study the oscillatory seabed response to wave loading, correspondingly residual seabed response is not considered. Therefore, the seabed response in the first wave period could reflect the seabed response to a newly-coming wave, which has not been dealt with in the previous studies. The seabed response in the second wave period corresponds to the seabed response to the succeeding wave train. Then, in seabed sub-model, we compiled the Biot's equations into COMSOL scripts via the PDE (Partial-Differential-Equation) module to govern the seabed response.

2. Theoretical formulations

In this section, the theoretical formulation of the proposed 3D model is firstly presented, including the wave model, seabed model, boundary condition and numerical scheme. The model of WSSI in the present study is sketched in Fig. 1. The breakwater is a slope breakwater with an underlying cushion. The breakwater head is a semicircle in top view and its slope is identical to that of the trunk. The seabed is taken as sandy deposits, thus Biot's theory for poro-elastic medium is available to model the seabed behaviour. In this study, the breakwater is considered to be armoured with impermeable layers. Hence, in this study, the breakwater is taken as an impermeable rigid object. The origin of Cartesian coordinates, point O, is located at the centre of aforementioned semicircle of the breakwater head. Points A, B, C, D and E are in the seabed with identical varying radius r, and wave-induced pore pressure at these points are used as indicators to reveal seabed response around the breakwater head. The ocean wave is propagating along the positive x-direction.

2.1. Wave model

In the model, the 3D RANS equations are solved for two incompressible phases using a finite volume discretization by OpenFOAM.

According to mass and momentum conservation, the incompressible fluid motion due to wave could be expressed in the form of Einstein summation convention:

$$\frac{\partial\langle u_{fi}\rangle}{\partial x_{fi}} = 0, \qquad (1)$$

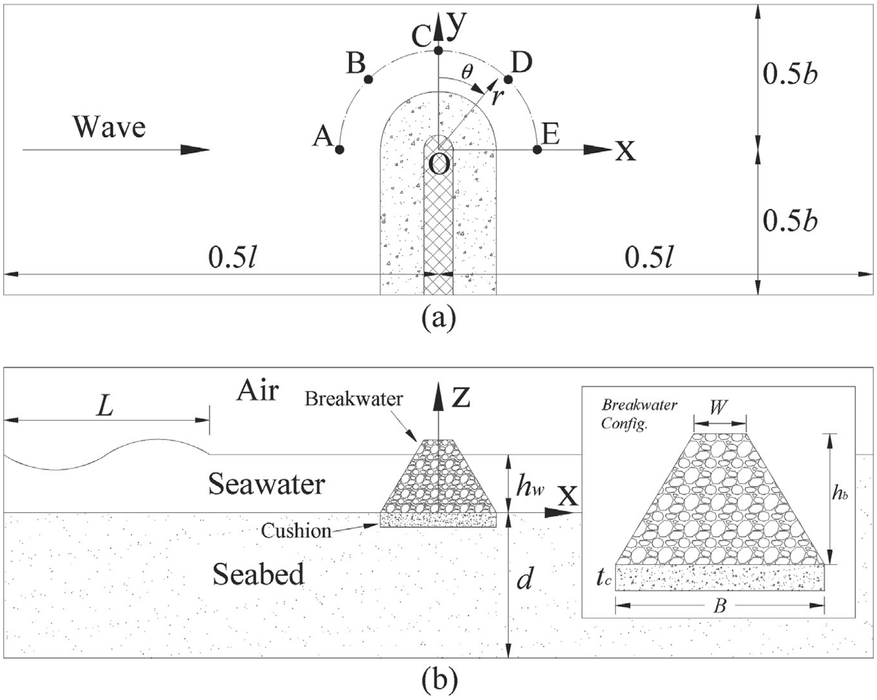

Fig. 1. Definition of WSSI around slope breakwater head: (a) plane view, (b) section view.