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Numerical modeling of the hydrodynamics of standing wave and scouring in front of impermeable breakwaters with different steepnesses

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ABSTRACT

The aim of this paper is to numerically study the effects of breakwater steepness on the hydrodynamics of standing wave and scouring process in front of impermeable breakwaters. A two-dimensional hydrodynamics model based on the Reynolds Averaged Navier–Stokes (RANS) equations and the Volume of Fluid (VOF) method was developed and then combined with an empirical sediment transport model. Comparisons with an analytical solution and experimental data showed the present model is very accurate in predicting the near bottom velocity and capable of simulating the scour/deposition patterns consistent with experimental data. It was found that the additional terms of bottom shear stress in the momentum equations are necessary to produce a physical scouring pattern. Different breakwater steepnesses produce different characteristics of standing wave, the steady streaming system, and scouring pattern in front of the breakwaters, which also affects the correlations between them. An additional analysis of the turbulence field parameters and the sediment transport rate was also performed. All these important information will be presented in details in this paper and can be worthwhile for designing the breakwater in coastal areas.

1. Introduction

Improvement of the role of coastal areas in supporting human life has driven development of various breakwaters around the coast for protection. The breakwater dissipates the energy of the waves incoming to the beach through a series of wave transformations for reducing their impact on the beach, especially during the storm conditions. The breakwater reflects a series incoming wave that impinges on it periodically. Then, the interactions of the incoming and reflected waves develop standing wave that consists of a series of nodes and antinodes in front of the breakwater. The standing wave on the surface produces the steady streaming, a system of recirculating cells below the surface (Tahersima et al., 2011; Yeganeh-Bakhtiary et al., 2010; Hajivalie et al., 2012). The steady streaming system is the key mechanism that is in charge for scouring in front of the breakwater.

One of the main concerns for coastal engineers in designing the breakwater is the stability. Local scour occurring in front of the breakwater is one of the main failure mechanisms (Sumer and FredsØe, 2000). The presence of sediment erosion and undesired deposition around the structure can threaten the breakwater stability and reduce its expected performance (Lee and Mizutani, 2008). Therefore, it is very important to understand the correlations between the characteristics of standing wave on the surface, the steady streaming system below it, and the scouring of sediment at the bottom. A better understanding of these correlations is worthwhile for the engineers to better design the breakwater.

The significance of scouring has triggered many researchers to assess the scour pattern around coastal structures. de Best and Bijker (1971) studied the problem of scouring of a sand bed in front of a vertical breakwater, and found the scouring patterns were different for fine and coarse materials. Xie (1981) studied the scouring pattern in front of a vertical breakwater and found the different shape of scouring pattern was dependent not only on the sand grain size but also on the wave conditions. Two basic patterns proposed by Xie (1981) have been widely used as the benchmark for studying scouring in front of a vertical breakwater. Irie and Nadaoka (1984), and Hughes and Fowler (1991) conducted

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other experimental studies for vertical breakwater, Lee and Mizutani (2008) for vertical submerged breakwaters, Sumer and FredsØe (2000) for rubble-mound (sloped) breakwater, and Sumer et al. (2005) for low-crested rubble-mound breakwater.

The wave- structure–sediment interactions play an important role in the development of scour. To study these interactions, three approaches are generally used, namely, small-scale physical models, theoretical approaches, and numerical models. Each approach has its own advantages and drawbacks, so none is sufficient by itself. Physical models can provide insights into a real flow-field environment; however, in many situations such works produce incomplete results due to many limiting factors. The limits of the experimental works are such as the high experimental cost, various field meteorological conditions, drawbacks of measurement tools, difficulties in implementing physical parameters, scale effects, etc. An extensive number of successful empirical formulations are available in the literatures (e.g. Whitehouse, 1998; Sumer and FredsØe, 2002). However, the empirical formulations cover only a limited number of wave conditions, setups, structure geometries, and sediment characteristics. These limits may lead to uncertainties and errors if they are used out of the range from which they are derived, which is a common problem faced in current design or pre-design conditions.

With the advancement of computer power today, the aforementioned limits are offset by developments and improvements of numerical models. Only the most recent numerical studies related to the present study are reviewed here. Gislason et al. (2009a,b) used a 3-D Navier–Stokes solver, NS3, with the k-ω, SST (shear stress transport) model to calculate flow under the standing wave. Then, they combined the model with a morphological model consisting of the continuity equation for sediment (FredsØe and Deigaard, 1992) and the bed-load equation (Engelund and FredsØe, 1976). They simulated the flow of standing wave and the scouring pattern in front of the vertical and sloped breakwaters. However, the result was slightly inconsistent with the experimental data for the scour profile in front of the sloped breakwater. Hajivalie and Yeganeh-Bakhtiary (2009) developed a numerical model consisting of the RANS equation, VOF method, and the k-ε turbulence model. They studied only the effects of breakwater steepness on the hydrodynamics of standing wave and the recirculating cells patterns. Yeganeh-Bakhtiary et al. (2010) used the same model to study the hydrodynamics of standing wave in front of a vertical breakwater. They focused on studying the effects of wave overtopping on the hydrodynamics of a standing wave, recirculating cells, and turbulence field. Then, Tahersima et al. (2011) coupled the hydrodynamics model of Yeganeh-Bakhtiary et al. (2010) with sediment transport formulae (Engelund and FredsØe, 1976; Bijker, 1971) and a bed profile change model (FredsØe and Deigaard, 1992) to study scouring in front of a vertical breakwater. They numerically showed the scouring patterns under the case of overtopping and without overtopping. However, the resulted patterns did not follow the scouring pattern of Xie (1981).

The above experimental and numerical studies have studied the hydrodynamics of standing wave and scouring pattern under the effects of four different factors. They are the wave conditions, breakwater shape, sediment grain size, and overtopping occurrence. Various numerical simulations have given more attention on the hydrodynamics of standing waves in front of the vertical/sloped breakwater. Only some of these studies extended the analysis by including the scouring at the bottom (Tahersima et al., 2011; Gislason et al., 2009a,b). However, these studies did not produce satisfying results. In addition, the experimental study for sloped breakwater (Sumer and FredsØe, 2000; Sumer et al., 2005) only provides limited descriptions on the important physical aspects. They are the characteristics of standing wave, the steady streaming system, and sediment transport process. In fact, a detailed description of such aspects is necessary to understand the effects of breakwater steepness on the correlations between them. Therefore, this paper is focusing to discuss more deeply the effects of breakwater steepness on the characteristics of standing wave, steady streaming system, and, in particular, scouring pattern.

The present model combines the RANS equations, VOF method, a k-ε turbulence closure model, and an empirical sediment transport formula of Bailard (1981). The model includes additional terms of bottom shear stress as used by Karambas (1998) in the momentum equations. As using the Bailard's formula, prior tests showed the terms of bottom shear stress are necessary to produce a physical scouring pattern. None of the RANS-based numerical models (Hajivalie and Yeganeh-Bakhtiary, 2009; Yeganeh-Bakhtiary et al., 2010; Tahersima et al., 2011) have taken these terms into their models. In addition, none of the previous scouring simulations (Tahersima et al., 2011; Gislason et al., 2009a,b) used the Baillard's formula. In this paper, it will be shown that the scouring patterns simulated by the present model are more consistent with the experimental results (Xie, 1981; Sumer et al., 2005) than the previous studies.

2. The numerical model

The present model used the SOLA-VOF code (Nichols et al., 1980) as the basic platform. However, some modifications and additional features were added into the code in order to make it more appropriate for simulating the interactions between wave, structure and sediment. This section presents the main components of the present model.

2.1. Governing equations of fluid flow

The Reynolds Averaged Navier–Stokes (RANS) equations were applied as the governing equations of fluid flow. The effect of turbulence was added into the governing equations in terms of the turbulent viscosity, which was calculated using the k-ε turbulence closure model. The momentum equations now include the additional terms of bottom shear stress as used by Karambas (1998). In two dimensional coordinates the governing equations are presented as follows:

$$\frac{\partial \theta u}{\partial x}+\frac{\partial \theta v}{\partial y}=0, \tag{1}$$

$$\frac{\partial \theta u}{\partial t}+\theta u\frac{\partial \theta u}{\partial x}+\theta v\frac{\partial \theta u}{\partial y}=\theta\frac{\partial}{\partial x}\left[2(\nu+\nu_t)\frac{\partial \theta u}{\partial x}\right]+\theta\frac{\partial}{\partial y}\left[(\nu+\nu_t)\left(\frac{\partial \theta u}{\partial y}+\frac{\partial \theta u}{\partial x}\right)\right] -\frac{\theta}{\rho}\frac{\partial p}{\partial x}-\frac{\tau_{bx}}{\rho}, \tag{2}$$

$$\frac{\partial \theta v}{\partial t}+\theta u\frac{\partial \theta v}{\partial x}+\theta v\frac{\partial \theta v}{\partial y}=\theta\frac{\partial}{\partial y}\left[2(\nu+\nu_t)\frac{\partial \theta v}{\partial y}\right]+\theta\frac{\partial}{\partial x}\left[(\nu+\nu_t)\left(\frac{\partial \theta v}{\partial x}+\frac{\partial \theta u}{\partial y}\right)\right] -\frac{\theta}{\rho}\frac{\partial p}{\partial y}-g-\frac{\tau_{by}}{\rho}, \tag{3}$$

$$\frac{\partial \theta k}{\partial t}+\theta u\frac{\partial \theta k}{\partial x}+\theta v\frac{\partial \theta k}{\partial y}=\frac{\partial}{\partial x}\left[\left(\nu+\frac{\nu_t}{\sigma_k}\right)\frac{\partial \theta k}{\partial x}\right]+\frac{\partial}{\partial y}\left[\left(\nu+\frac{\nu_t}{\sigma_k}\right)\frac{\partial \theta k}{\partial y}\right]P_r-\varepsilon, \tag{4}$$

$$\frac{\partial \theta \varepsilon}{\partial t}+\theta u\frac{\partial \theta \varepsilon}{\partial x}+\theta u\frac{\partial \theta \varepsilon}{\partial y}=\frac{\partial}{\partial x}\left[\left(\nu+\frac{\nu_t}{\sigma_\varepsilon}\right)\frac{\partial \theta \varepsilon}{2\partial x}\right]+\frac{\partial}{\partial y}\left[\left(\nu+\frac{\nu_t}{\sigma_\varepsilon}\right)\frac{\partial \theta \varepsilon}{\partial y}\right] +C_{\varepsilon 1}(P_r)\frac{\varepsilon}{k}-C_{\varepsilon 2}\varepsilon\frac{\varepsilon'}{k} \tag{5}$$

$$P_r=\nu_t\left[2\left(\frac{\partial \theta u}{\partial x}\right)^2+2\left(\frac{\partial \theta v}{\partial y}\right)^2+\left(\frac{\partial \theta u}{\partial y}+\frac{\partial \theta v}{\partial x}\right)^2\right], \tag{6}$$