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The effects of wave activity on overtopping and scouring on a vertical breakwater

N. Tofany [a,*], M.F. Ahmad [b], M. Mamat [c], H. Mohd-Lokman [a]

[a] School of Marine Science and Environment, Universiti Malaysia Terengganu, Malaysia
[b] School of Ocean Engineering, Universiti Malaysia Terengganu, Malaysia
[c] Faculty of Informatics and Computing, Universiti Sultan Zainal Abidin, Malaysia

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ABSTRACT

A numerical study is presented herein to investigate the effects of wave activity on overtopping discharges and scouring offshore of a vertical breakwater. A 2D RANS-VOF model was used to study this topic. The model was coupled with turbulence closure, sediment transport, and morphological models with additional bottom shear stresses in the momentum equations. Validation results show that the numerical predictions of velocities are in good agreement with the experimental data and the analytical solution. The predicted scour patterns and maximum equilibrium scour depths also show better accuracy than the results of existing models. Numerical experiments were then conducted by varying wave and breakwater height (freeboard) which result in different overtopping discharges. The effects of different wave heights and freeboards on the overtopping discharge, and the subsequent effects on the hydrodynamics and scouring were analyzed. The results of this analysis will be discussed in details in this paper and are expected to be worthwhile in the process of designing breakwater in coastal areas.

1. Introduction

Complex interactions between waves and a breakwater generate phenomenon that may induce undesired scour offshore of the breakwater. The inducing phenomenon are such as standing waves, vortices, wave reflections, breaking waves, turbulence flow, etc. A substantial scour hole at the toe of a breakwater (toe scouring) can damage its structure and thus threatens the safety of the protected areas behind it. Nine research institutions from six European countries, even considered the serious threat of scour through extensive field and laboratory studies under the project of Scour Around Coastal Structures (SCARCOST). The results are summarized by Sumer et al. (2001). Another study by the US Army Corps of Engineers (Lillycrop and Hughes, 1993) also reported various failure mechanisms of breakwaters due to scour. The results can be reviewed in the paper of Oumeraci (1994). Therefore, understanding the formation of scour and the inducing mechanisms is highly important research topic.

Standing waves are one of the main inducing mechanisms for the toe scouring formed offshore of vertical breakwaters. Müller et al. (2008) reported that toe scouring is attributed to wave reflections which increase wave heights (through the formation of standing waves), velocities and turbulence. Depending on the reflected wave characteristics, standing waves may vary from fully or partially as studied by Young and Testik (2011). In addition to the toe scouring, Allsop et al. (2005) and Müller et al. (2008) reported that wave overtopping is the critical response of vertical breakwaters. Yeganeh-Bakhtiary et al. (2010) and Tahersima et al. (2011) showed that wave overtopping is significant in changing the characteristics of reflected waves and scour patterns offshore of the breakwater. In other studies (Xie, 1981; Lee and Mizutani, 2008), wave conditions and breakwater height have been reported as the important factors on the hydrodynamics and scour patterns generated offshore of vertical breakwaters. These findings lead to a question of what will happen on the hydrodynamics and scour patterns offshore of the vertical breakwaters if these two factors are considered as the factors that influence the rate of overtopping discharge. The present study is conducted to investigate this issue.

A number of researchers had conducted the experimental works of scouring around the breakwaters. The problem of scour offshore of a vertical breakwater was early studied by de Best and Bijker (1971) and Xie (1981). They found that scour patterns were different for fine and coarse materials. Xie (1981) proposed two basic scour patterns. The patterns are now widely used as the reference patterns for studying scour offshore of a vertical breakwater. The other experimental studies are such as Irie and

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[*] Correspondence to: School of Marine Science and Environment, Universiti Malaysia Terengganu, 21030 Kuala Terengganu, Terengganu, Malaysia. Tel.: +60 9 6683236.
E-mail addresses: novan.tofany@umt.edu.my, novtov354@gmail.com (N. Tofany).

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Nadaoka (1984), Hughes and Fowler (1991) for vertical breakwaters, Sumer and Fredsøe (2000) for rubble mound breakwaters, Sumer et al. (2005) for submerged sloped breakwaters, and Lee and Mizutani (2008) for vertical submerged breakwaters. These studies also showed that the re-circulating cells of steady streaming formed under standing waves have significant effects on the formation of scour. The effects of overtopping on the hydrodynamics of standing waves were specifically studied by Zhang et al. (2001). They measured the maximum horizontal velocity of water particles near the node of standing waves offshore of a vertical breakwater. It was shown that overtopping decreased the maximum horizontal velocity of fluid particles.

Numerical studies investigating scour under the influence of overtopping are relatively rare. Notable studies include Yeganeh-Bakhtiary et al. (2010) and Tahersima et al. (2011) that numerically studied the overtopping effects on the hydrodynamics of standing waves and scour offshore of vertical breakwaters. Yeganeh-Bakhtiary et al. (2010) studied the hydrodynamics aspects using a model based on the Reynolds Averaged Navier Stokes (RANS) equations and Volume of Fluid (VOF) method. Tahersima et al. (2011) coupled the model with the sediment transport formulae of Engelund-Fredsøe (1976) and Bijker (1971) and a morphological model of Fredsøe and Deigaard (1992) to simulate the scouring process, although limitations were evident in the scour simulations when compared to the result of Xie (1981). Gislason et al. (2009a,b) used the same sediment transport models as used by Tahersima et al. (2011) which coupled with a 3D Navier–Stokes solver and a k–ω turbulence model. Their simulated scour pattern was in good agreement with the experimental data of Sumer et al. (2005) for the vertical breakwater case, yet it was not accurate in the sloped breakwater case. Hajivalie et al. (2012) applied an Euler–Lagrange modeling approach for the simulation of scour offshore of a vertical breakwater. Although their simulated scour patterns could resemble the pattern of Xie (1981), however, the effects of overtopping were beyond the scope of their study. In addition, none of these studies have ever investigated the effects of different overtopping discharges. This unexplored issue and the lacks of existing numerical results have produced a gap of knowledge on the hydrodynamics and scour offshore of vertical breakwaters. The present study is therefore conducted to bridge this gap.

In the present work, the two-dimensional numerical model of Tofany et al. (2014) is applied to study the effects of different overtopping discharges on the hydrodynamics and scour patterns offshore of vertical breakwaters. The model combines the hydrodynamic model, consisting of the RANS equations, VOF method, and a k–ε turbulence model, with the sediment transport formula of Bailard (1981) and the morphological model of Fredsøe and Deigaard (1992). Additional terms of bottom shear stress as used by Karambas (1998) are added into the momentum equations. There has not been any study that ever used this modeling approach to the present simulation problem.

Tofany et al. (2014) have shown that the numerical results of this model were encouraging. The computed near bottom velocities were found in close agreements with the experimental data and analytical solution. Although the model did not simulate the scour/deposition pattern in the equilibrium state, the simulated patterns showed better agreement with the patterns as found in the experimental results of Xie (1981) and Sumer et al. (2005) than the numerical results of Tahersima et al. (2011) and Gislason et al. (2009b). It was also interesting to find that the additional terms of bottom shear stress were significant to produce physical scour patterns, because without these terms in the model, the physical scour patterns could not be obtained. The model was also successfully applied to extend the knowledge of breakwater steepness effects on the hydrodynamics and scouring offshore of sloped impermeable breakwaters (Tofany et al., 2014).

In this study, two numerical experiments were conducted to investigate the effects of wave overtopping and different overtopping discharges due to different wave conditions and breakwater heights (freeboards). Validation results of the model for fluid velocities and equilibrium scour patterns are presented earlier. The results of the numerical experiments showed that overtopping reduces the energy of the reflected waves. Consequently, the intensity of re-circulating cells offshore of the breakwater is decreased and thus reduces the sizes of scour depths/deposition ridges. It even prevents the toe scouring to develop offshore of the breakwater, in which the scour at this area can affect the breakwater stability. It was also found that wave characteristics, intensity of the re-circulating cells, and sizes of the scour depths/deposition ridges are highly affected by the rate of overtopping discharge. The detailed discussion will be presented in this paper.

2. The numerical model

Tofany et al. (2014) developed the 2D RANS-VOF model by modifying the SOLA-VOF code. The SOLA-VOF code is a solution algorithm for various cases of transient fluid flows involving free surface motions. The code provides important components required for the present simulation such as the two-dimensional incompressible Navier–Stokes equations for describing the flow field, the Volume of Fluid (VOF) method for tracking free surface motions, and other features that can be seen more detail in Nichols et al. (1980). Some modifications were made to the original code to make it more suitable for simulating the wave–structure–sediment interactions. The following describes the main components of the present model after modifying the original code.

2.1. Governing equations

The governing equations of fluid flow are the RANS equations and the k–ε turbulence closure model. The additional bottom shear stresses of Karambas (1998) are included in the momentum equations using. In a two-dimensional domain, the equations are given as follows:

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

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

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

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

$$\frac{\partial \theta \varepsilon}{\partial t}+\theta u\frac{\partial \theta \varepsilon}{\partial x}+\theta \nu\frac{\partial \theta \varepsilon}{\partial y}=\frac{\partial}{\partial x}\left[\left(\upsilon+\frac{\upsilon_t}{\sigma_\varepsilon}\right)\frac{\partial \theta \varepsilon}{2\partial x}\right]+\frac{\partial}{\partial y}\left[\left(\upsilon+\frac{\upsilon_t}{\sigma_\varepsilon}\right)\frac{\partial \theta \varepsilon}{\partial y}\right] +C_{\varepsilon 1}(P_r)\frac{\varepsilon}{k}-C_{\varepsilon 2}\varepsilon\frac{\varepsilon}{k}, \tag{5}$$

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