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Numerical simulation of wave propagation over submerged reef

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HIGHLIGHT

Wave transformation over a submerged reef was investigated numerically using OpenFOAM. The numerical model was validated against the physical experimental data, and it has shown that the model is capable of simulating the key processes of wave shoaling, breaking and transmission over the submerged reef. A series of new numerical studies were conducted considering different incident wave heights, submergences and slopes of the reef. The influences of reef slope and submergence on the wave properties over the reef are discussed.

1 INTRODUCTION

Submerged reef bathymetry is characterized by a steep slope and a shallow platform. As waves propagate from deep water to reefs, the rapid decreasing of water depth causes wave reflection, shoaling and breaking. The hydrodynamics of these complex processes are different from those occurring in gentle or mild slopes.

OpenFOAM is one of the widely used CFD models in coastal and offshore engineering applications (Morgan et al. 2010; Higuera et al. 2013; Jacobsen et al 2012; Chen et al. 2014). In this work, it is used to better understand wave propagation and transformation on reef bathymetry. It solves the Navier-Stokes equation which completely describes water wave hydrodynamics, and combines the Volume Of Fluids (VOF) method to model the complex free surface. The *k-w* SST turbulence model is used to simulate wave breaking and the wave generation library waves2Foam is adopted to generate waves in the model.

2 NUMERICAL METHODS

The governing equations in the current numerical model for two-phase incompressible flows are the Reynolds-Averaged Navier-Stokes equations:

$$\frac{\partial \rho \mathbf{u}}{\partial t} + \nabla \cdot [\rho \mathbf{u}\mathbf{u}^T] = -\nabla p + \rho \mathbf{g} + \nabla \cdot [\mu \nabla \mathbf{u} + \rho \boldsymbol{\tau}] \qquad (1)$$

$$\nabla \cdot \mathbf{u} = 0 \qquad (2)$$

Here, $\mathbf{u}$=(u, v, ω) is the velocity field, p is the pressure, ρ is the density, $\mathbf{g}$ is the gravitational acceleration and μ is the dynamic viscosity. $\boldsymbol{\tau}$ is the specific Reynolds-stress tensor:

$$\boldsymbol{\tau} = 2\nu_t \mathbf{S} - \frac{2}{3} k \mathbf{I} \qquad (3)$$

where ν_t is the turbulent viscosity, $\mathbf{S}$ is the strain rate tensor ($1/2(\nabla \mathbf{u} + (\nabla \mathbf{u})^T)$), k is the turbulent kinematic energy and $\mathbf{I}$ is the identity matrix.

In order to specify the turbulent viscosity ν_t and to close the above equations, the k-ω SST model is used in the current model. The surface is captured by the volume of fraction (VOF) scheme and

Waves2Foam (Jacobsen et al., 2012) was used for generating the incoming wave. The relaxation zone was implemented to avoid wave reflection from both inlet and outlet.

3 VALIDATIONS

An experiments performed at DUT was used to validate the numerical model. The sketch of this experimental set-up is shown in Fig. 1. The flume is 69.0 m long, 2.0 m wide and 1.8 m deep. The experimental water depth h_0 is 0.715m. The height of the submerged reef plat was 0.5m, and the depth at the reef plat h_r is 0.215m. The steep slope of 1:5 was adopted in this experiment. Three waves have the same wave period T=2.0s a different wave heights H= 0.10m, 0.14m and 0.20m, were simulated. They represent the spilling breaker, plunging breaker and violently plunging breaker, respectively.

Fig.2 shows the comparisons of free surface time series between numerical results and experimental data. In fig. 2(a), wave height is the smallest one, the whole wave propagation process, including wave shoaling, wave breaking and strong nonlinear interactions, is well captured by the numerical model. In fig. 2(b), despite that there is larger breaker and stronger nonlinear interactions, the numerical model still predicts the free surface elevations well, compared to the experimental measurements. Fig. 3 presents the comparisons of the average wave heights between numerical results and experimental data. It can also be seen that the present numerical model predicts the wave height accurately.

4 RESULTS AND DISCUSSION

In order to investigate the properties of wave transformation over the reef topography, various wave heights, slopes and submergences of the reef are considered and simulated. The wave conditions are listed in Tab. 1. Three different slopes tanα are adopted: 1:2, 1:5 and 1:15, respectively. The height of the reef is 0.5m, three different submergences h_r and water depth ratio $\varepsilon = h_r/h_0$ are used. A series of monochromatic wave with various wave heights H_0 from incipient breaker to violent breaker were generated.

The relative breaking wave height defined as the ratio of the breaking wave height H_b and incident wave height H_0 in deep water, is an important criterion to describe the wave breaking. Fig.4 gives the relationship between the relative breaking wave height and deep-water wave steepness H_0/L_0 for all the simulated wave cases. The theoretical results of Munk(1949), the modified Munk's formular by Komar and Gaughan(1972) and the empirical formula from the experimental study by Xu et al.(2017) are also given in the figure for comparison. It clearly shows that the relative breaking wave height depends on the deep-water wave steepness. Also, it can be seen that the numerical results deviate from the results of Munk (1949) and Komar and Gaughan (1972). While, there is a good agreement between the numerical results and the empirical formula of Xu et al. (2017).

The influences of the reef slope and submergence on the wave induced setup are illustrated in Fig.5. Fig. 5 gives the variation of the non-dimensional wave setup $\bar{\eta}/(T\sqrt{gH_0})$ and the non-dimensional submergence considering the wave setup $(\bar{\eta}+h_r)/H_0$ for all the numerical cases. The figure shows that there are strong correlations between the wave setup and submergence. The wave setup increases with decreasing non-dimensional submergence. Based on our numerical results, a fitting curve that predicts the wave setup can be written as:

$$\frac{\bar{\eta}}{T\sqrt{gH_0}} = 0.008\left(\frac{\bar{\eta}+h_r}{H_0}\right)^{-2.0} \qquad (4)$$

The formula indicates that the wave induced setup on the reef flat is mainly controlled by reef submergence and wave height for fixed wave period.

5 CONCLUSIONS

The OpenFOAM model was verified that it is reliable to simulate the process of wave shoaling, breaking and transmission on the reef. Further, a series of numerical experiments are conducted considering various reef slope and submergence of reef. The results show that the relative breaking wave height depends on the deep-water wave steepness. The wave induced setup on the reef flat is mainly controlled by the reef submergence and the incident wave steepness. Based on the present numerical results, an empirical formula is proposed to predict the wave induced setup on the reef flat.

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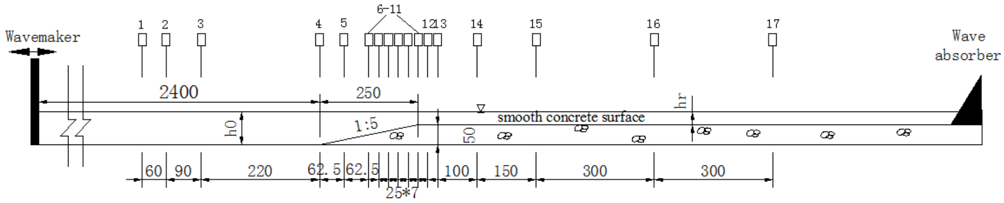
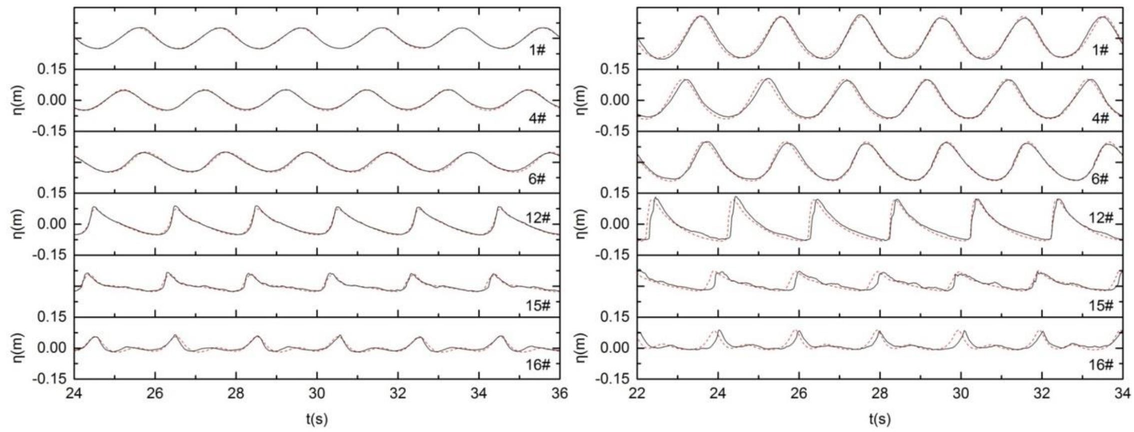


Fig.1 The sketch of experimental set-up (Unit: cm)



(a) T=2.0s, H=0.10m **(b) T=2.0s, H=0.20m**

Fig 2. Time history of the surface elevation at different locations. Black solid lines: experimental results; red dashed line: numerical results.

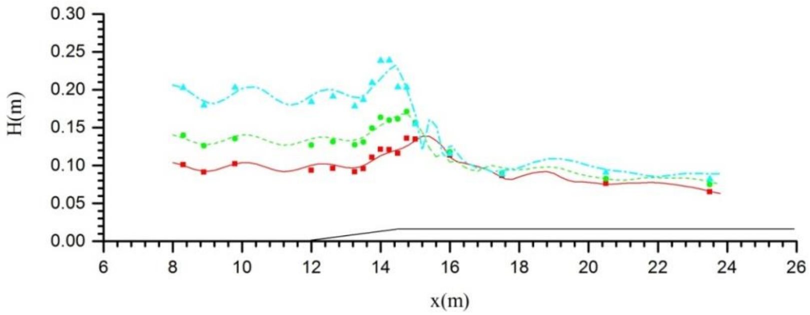


Fig 3. The comparisons of the average wave heights between numerical results (line) and experimental results (scatter) for different cases (Red: H=0.10m, Green: H=0.14m, Blue: H=0.20m).

Table 1 The summary of wave conditions used in the numerical simulation

h_r(m)	$\varepsilon = h_r/h_0$	tanα	H_0(m)
0.125	0.2	1:5	0.06~0.16
0.215	0.3	1:2, 1:5, 1:15	0.08~0.24
0.335	0.4	1:5	0.14~0.26

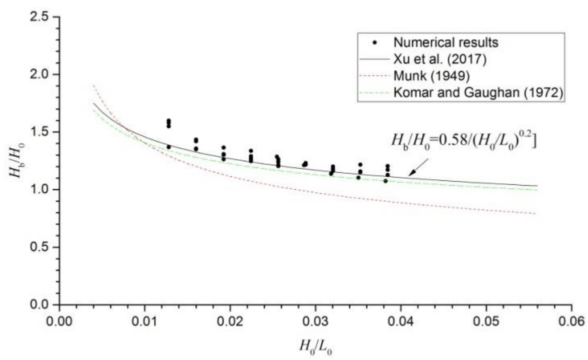


Fig. 4 Comparisons between the numerical relative breaking wave heights with the theoretical formula.

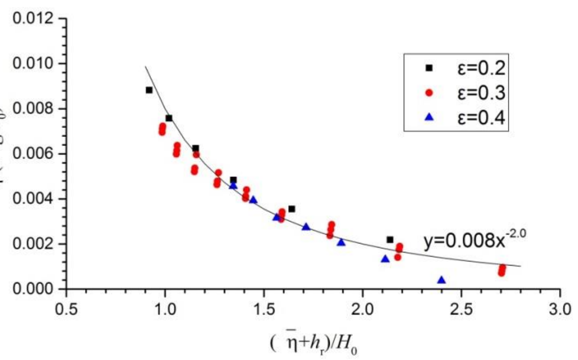


Fig.5 The relationships between the non-dimensional wave setup and submergence.