

EFFECTS OF WAVE BREAKING AND BEACH SLOPE ON TOE SCOUR IN FRONT OF A VERTICAL SEAWALL

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Scour in front of coastal structures is a major threat to structural stability and safety of properties behind. In this study, a Reynolds Averaged Navier-Stokes Solver (RANS) is combined with a Volume of Fluid (VOF) (RANS-VOF) surface capturing scheme to investigate the wave interactions with a Seawall and its adjacent sea bed. The main objective is to investigate the effects of wave breaking and beach slope on toe scour in front of a vertical wall.

Keywords: Vertical Seawall, beach lowering, toe scour, standing wave, breaking wave, RANS

INTRODUCTION

Scour in front of coastal structures is a vital threat to structural stability and safety of properties behind. Wave breaking is believed to be a significant factor in sediment transport and beach profiles changes. The experimental study by Fredsøe and Sumer (1997) indicates that the steady streaming generates a scour hole in front of a breakwater while the plunging breaker generates a scour hole at the lee-side of the breakwater. Tsai et al. (2009) studied the toe scour of seawalls on a beach slope of 1:5 under regular waves in the lab. They concluded that the scour depth induced by a plunging breaker is larger than that by a spilling breaker or a non-breaking wave.

In case of non-breaking waves, Sumer and Fredsoe, (2002) and Sumer (2007) found that the reflection from the breakwater forms a standing wave which generates the steady streaming in front of breakwater, consisting of bottom and top recirculating cells. The formation of bottom cell is related to the boundary layer over the bed and the sediment motion on the bed responds to these recirculating cells. Consequently a scour /deposition pattern in front of the breakwater emerges in the form of alternating scour and deposition areas lying parallel to the structure. However, in case of breaking waves, Sumer (2007) mentioned that the complex process of wave breaking generates a strong downward flow in the form of a jet to erode the bed and mobilize the sediment at the toe of vertical wall, which presumably leads to scour at the toe of a seawall.

Gislason et al. (2009) investigated the two-dimensional scour and deposition in front of vertical and sloping Seawalls using a 3-D Navier-Stokes solver, coupled with a $k-\omega$ turbulence model and a morphologic model. They reproduced the well known alternating scour/deposition pattern in front of the breakwater (e.g., Sumer and Fredsoe, 2002). However, effect of wave breaking is not considered in their work. In their Study, the free surface is tracked by integrating in time the kinematic boundary conditions based on the free surface volume flux.

In this study, a Reynolds Averaged Navier-Stokes Solver (RANS) combined with a Volume of Fluid (VOF) surface capturing scheme is used to simulate the hydrodynamics of wave interactions with a seawall. This model is further coupled with a bed-load sediment transport equation and morphological model in order to predict beach profile changes in front of the seawall. The main objective is to investigate the effects of wave breaking and beach slope on toe scour in front of a vertical wall.

EXPERIMENTS

Medium scale physical model tests of scour in front of seawalls were performed in the wave flumes (45 m (L)×1.2 m (W)×1.7 m (H)) at HR Wallingford in the UK (HR Wallingford, 2006, Sutherland et al 2006)). Waves were generated using a piston-type wave maker with maximum stroke of ± 0.6 m and maximum operating depth of 1.4 m. Test setup had a 19.2 m long 1:30 smooth concrete slope from the flume floor up to an elevation of 0.64m. Test section was a 5.14 m long sand bed filled with Redhill 110 sand. Mean sand diameter, $d_{50}=0.111$ mm, kinematic viscosity $\nu=1\times 10^{-6}$ m²/s and sediment density $\rho_s=2650$ kg/m³. More details about the experiment can be found in Sutherland et al. (2006). In

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this study, these experiments will be used to validate the model simulation of toe scour in front of a vertical Seawall on a sloping beach.

NUMERICAL MODEL

Hydrodynamic model

The Reynolds Averaged Navier-Stokes-Volume of Fluid (RANS-VOF) model, developed by Lin and Liu (1998), solves the Reynolds-Averaged Navier-Stokes equation for the mean flow field and the non-linear $k-\epsilon$ equations for the turbulent kinetic energy, k , and the turbulence dissipation rate, ϵ . The Volume of Fluid method is employed to capture free surface. During the computation, a no-slip boundary condition at the solid boundaries and a zero-stress condition at the free surface are employed. Turbulent kinetic energy, k , and dissipation rate, ϵ , are assumed to be a function of distance from the solid surface and have zero gradient at the free surface. An active wave generating-absorbing wave-maker located at the inlet is applied to generate waves and simultaneously absorb the reflected waves from the structures (Troch and De Rouck, 1999). More detailed information about the model can be found in Lin & Liu (1998) and Peng and Zou (2011). Recently this model has been further developed and used widely to investigate wave-structure interactions and subsequent coastal flood risk (Garcia et al. 2004; Lara et al. 2006; Zou & Peng 2011; Zou et al 2012)

The cell size in the y-direction varies from 0.01 m in the near bed region to 0.02 m away from the bed. The cell size in the x-direction is 0.05 m. Numerical model setup is illustrated in Figure 1. RANS-VOF model has been extended to deal with complex bathymetry, such as a ripple bed in this study. In the original code, the bathymetry is defined by a series of conic sections whose equations are provided by the user. This treatment is too tedious for large and complicated bathymetry. In the updated code, complicated bathymetry can be read directly from an input file.

Sediment transport model

Due to the complexity and uncertainty of sediment transport, empirical formulae based on experiments have been implemented to describe this process in previous studies (e.g., Pedrozo-Acuña et al., 2006; Bakhtyar et al., 2009). Madsen (1991) introduced a formula based on the work by Meyer-Peter and Muller (1948), which accounts for slope corrections and the angle of repose.

$$\frac{q(t)}{\sqrt{(s-1)gd_{50}^3}} = \frac{C}{1 + \frac{\tan \beta}{\tan \phi}} (\theta - \theta_{cr})^{3/2} \frac{u_b}{|u_b|} \quad (1)$$

where $q(t)$ is instantaneous sediment transport rate; $s=\rho_s/\rho$ is the specific density, where ρ_s is the grain density and ρ is the water density; d_{50} is the mean grain diameter, g is the gravity; C is sediment transport efficiency; β is the beach slope and Φ is the angle of repose; u_b is the instantaneous free stream velocity close to bed. $\theta = \frac{0.5 f u_b^2}{(s-1)gd_{50}}$ is the shields parameter, f is the bottom friction factor.

This formula has been widely used in the swash zone of sandy beaches (e.g., Butt and Russell, 2000; Larson et al., 2001) and therefore it will be employed in this study to obtain the sediment transport rate.

A threshold shear stress for sediments on a sloping bed at angle β to the horizontal bed, is related to the direction of horizontal component of near-bed flow, for flow in the up- and down- slope direction respectively.

$$\theta_{\beta c} = \theta_{co} \cos \beta \left(1 - \frac{\tan \beta}{\tan \phi}\right) \quad (2)$$

$$\theta_{\beta c} = \theta_{co} \cos \beta \left(1 + \frac{\tan \beta}{\tan \phi}\right) \quad (3)$$

where θ_{bc} is the critical value of θ for the initiation of sediment motion at the sloping bed and θ_{co} is the critical shields parameter for the initiation of sediment motion on a horizontal bed. θ_{co} is a function of the grain Reynolds number (Sumer and Fredsøe, 2002, p.10) and it is approximately 0.06 in this study.

The theoretical expression for the friction factor can be approximated by (Fredsoe and Deigaard, 1992)

$$f = \begin{cases} 0.04\left(\frac{a}{k_N}\right)^{-\frac{1}{4}}, & \frac{a}{k_N} > 50 \\ 0.4\left(\frac{a}{k_N}\right)^{-\frac{3}{4}}, & \frac{a}{k_N} < 50 \end{cases} \quad (4)$$

where k_N is bed roughness length (around 1/12 of grain size), and $a = U_0 * T / 2\pi$, bottom free stream velocity, U_0 is taken as the maximum value of the measured velocity at 5cm above the bed and T is incident wave period.

Morphology model

The bed profile is updated by solving the sediment conservation equation based on the time-averaged sediment transport rates from a bed-load sediment transport equation (1) (Fredsøe and Deigaard, 1992, chapter 11):

$$\frac{\partial q(t)}{\partial x} = -(1-n) \frac{\partial z}{\partial t} \quad (5)$$

where z is the bed level and n is the beach porosity, $n=0.44$ is used in this study. The sand-slide model of Liang and Cheng, (2005) is modified and used to resolve the avalanching process and five-point Gaussian average is applied to the newly updated bed levels to smooth out the small-scale bed features.

MODEL RESULTS

The model is validated against the toe scour experiment for a regular wave on a flat bottom in front of a vertical wall, described in Gislason et al. (2009). The model prediction of bed profile are in a good agreement with the measurements after 300 waves. Model is then setup in the same way as the toe scour experiments of random waves over a sloping bed by Sutherland et al (2006) (cf. figure 1). The vertical wall is located at $x=28$ m in figure 1. The model-data comparisons are used to study the toe scour over a sandy beach with a 1:30 slope in front of a vertical wall, with particular attention to the effects of wave breaking and water depth. Random waves are generated using the JONSWAP spectrum. Table 1 shows the key parameters for 3 examples model results out of numerous test runs conducted.

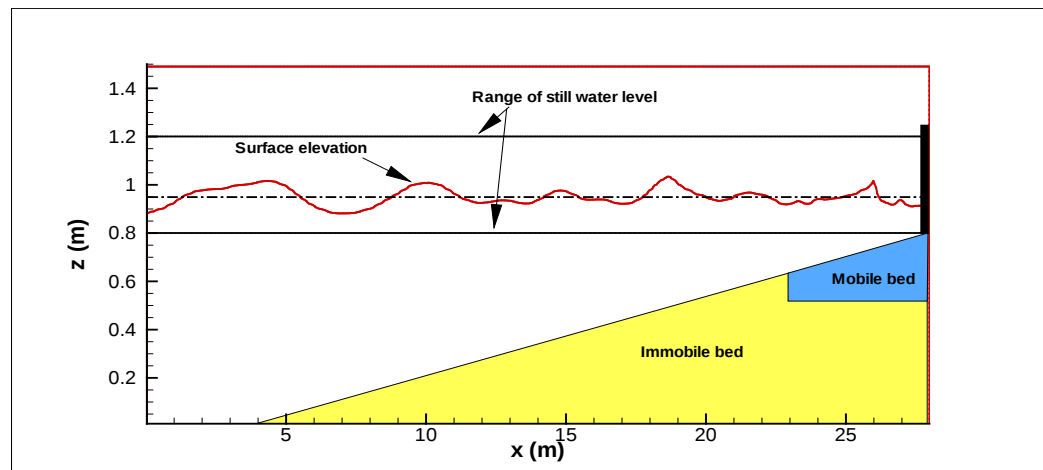


Figure 1 Numerical model setup and computation domain

Table 1. Examples test runs for toe scour on a sloping beach				
Case No.	H_s	T_p	h_0	h_{toe}
1	0.2	3.24	0.95	0.1
2	0.2	1.87	1.0	0.2
3	0.2	1.87	1.25	0.4

Case 1: low water level

Random waves were generated from Jonswap spectrum with significant wave height $H_s=0.2$ m, peak wave period $T_p=3.24$ s, deep water depth $h_0=0.95$ m and water depth at the toe of the wall $h_{toe}=0.1$ m. Figure 2 indicates that the predicted wave height is in a good agreement with the observation. As shown in figure 2, the wave height remains almost the same from $x=0$ to $x=23$ m and decreases dramatically shoreward from $x=23$ m, indicating this location is the wave breaking point for most wave components. As the wave approaches the wall further, the wave height increases again at a location closer to the vertical wall ($x=28$ m). The reflected wave from the vertical wall leads to partial standing wave and thus larger wave height in this area.

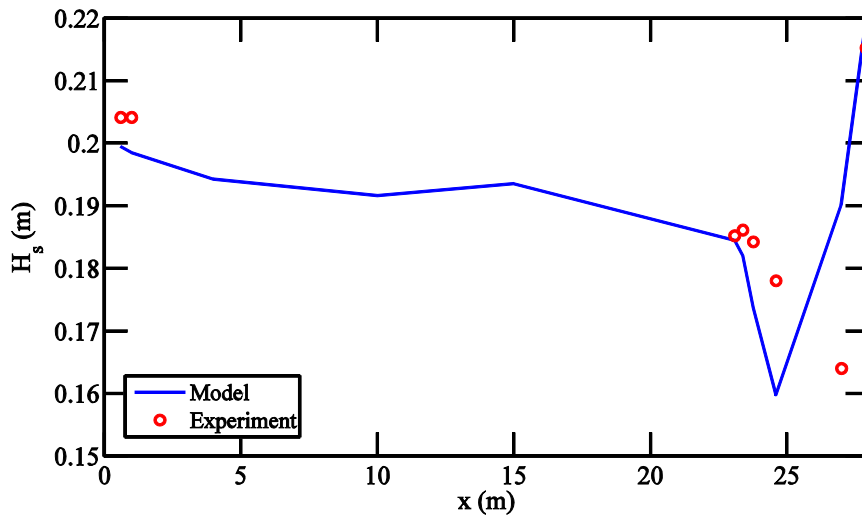


Figure 2 Model-data comparison of cross shore evolution of significant wave height.

The beach profile evolves from the initially smooth profile (black dotted line) to an undulating profile (blue dashed line) in figure 3. There is a large scour area close to the vertical wall followed by a small deposition area immediately seaward. Waves tend to break offshore so that wave energy is largely dissipated before reaching the Seawall. Scour is mainly induced by the near bottom offshore current generated by the breaking and the partial standing waves adjacent to the wall. The beach profile and scour and deposition pattern agrees reasonably well with measurements. The calculated maximum scour depth and deposition also compare well with the measurements.

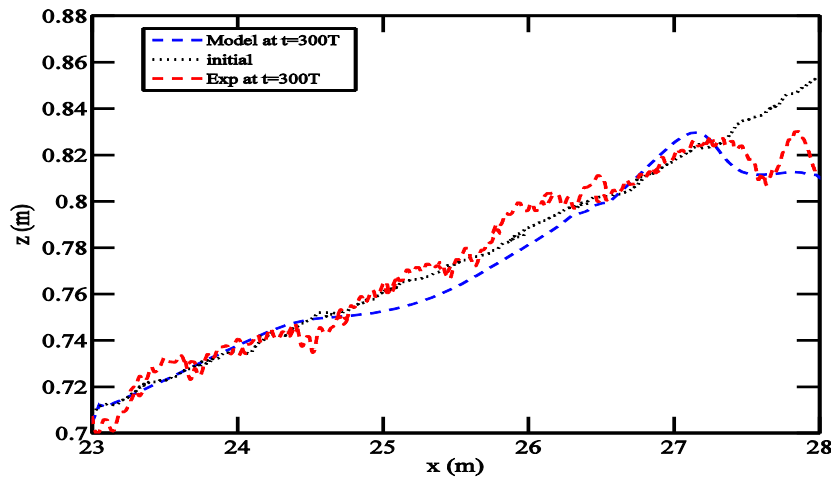


Figure 3 Comparison of model predicted scour and deposition with measurements for case 1 $H_s=0.2\text{m}$, $T_p=3.24\text{s}$, $h_{toe}=0.1\text{m}$.

Case 2: mid water level

Random waves were generated from Jonswap spectrum with significant wave height $H_s=0.2\text{ m}$, peak wave period $T_p=1.87\text{ s}$, water depth at the toe of the wall $h_{toe}=0.2\text{ m}$. As can be seen from Figure 4, the predicted beach profile as well as the calculated maximum scour depth and deposition agrees well with the measurement after 300 waves. The initial beach profile is taken from the measurements. Compared with Case 1 results in Figure 3, Figure 4 shows that the horizontal extent of the toe scour decreases for smaller incident wave period and slightly larger water depth in Case 2. The offshore boundary of scour zone is at $x=27.4\text{ m}$ for $T_p=1.87\text{ s}$ in Case 2 and at $x=27\text{ m}$ for $T_p=3.24\text{ s}$ in Case 1. Both the model and experiment indicate a significant deposition just seaward of the scour area for Case 2. These differences between Case 2 and Case 1 is mainly due to the change in the relative water depth at the toe of the vertical wall, i.e., the relative water depth, h_{toe}/L_{deep} , is 0.042 for $T_p=1.87\text{ s}$, Case 2 and 0.01 for $T_p=3.24\text{ s}$, Case 1. The intermediate water depth in this case allows bigger waves to arrive at the structure without breaking. The bigger waves in turn generate larger scour and deposition at the structure.

Given this wave condition, similar to the laboratory observations by Sutherland (2006), our model simulation shows that waves tend to break onto the structure and a partial standing wave is formed inside the surf zone. Our model results also indicate that water plunging upon the face of the seawall to the bed and produce strong vortex, streaming velocity and turbulence near the wall, resulting in the deepest scour depths and depositions.

Case 3: high water level

Random waves were generated from Jonswap spectrum with significant wave height $H_s=0.2\text{ m}$, peak wave period $T_p=1.87\text{ s}$, water depth at the toe of the wall $h_{toe}=0.4\text{ m}$. In contrast with Case 1 and 2 shown in figures 3 and 4, the bed profile change is small and undulated with alternating scour and deposition pattern. This is mainly due to the larger water depth at the toe of the vertical wall in this test case. There is little wave breaking and the near bottom velocity is not large enough to move significant amount of sediment within the mobile bed area (Figure 1), and therefore there is small scour depth and deposition.

CONCLUSIONS

Present model can reproduce the observed scour and deposition processes in front of a seawall on a flat bottom and a sloping beach. In the presence of beach slope, the strength and spatial distribution of streaming velocity and bottom orbital velocity along the seabed are altered significantly by the wave randomness, wave breaking type and location, as well as the breaking induced wave reflection. The former largely determines the magnitude and direction of sediment transport. In particular, the breaking location and type are key factors in scour formation. At low water depth, wave breaks offshore, a partial standing wave and relatively small toe scour occurs at the wall. At intermediate water depth, the

deepest scour depth is found in case of plunging breaker on the wall. At large water depth, very little breaking happens and near bottom velocity is not large enough to move significant amount of sediment within the mobile bed area so that scour and deposition are minimum. Model result also indicates that the extent of scour area increases with the wave period.

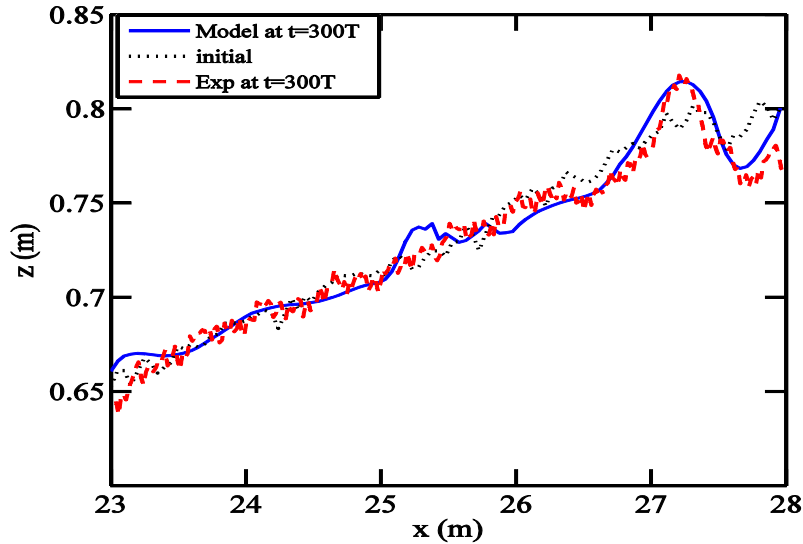


Figure 4 Calculated Beach profile at $t/T=50$ and measured beach profile for $H_s=0.2\text{m}$, $T_p=1.84\text{s}$, $h_{toe}=0.2\text{m}$

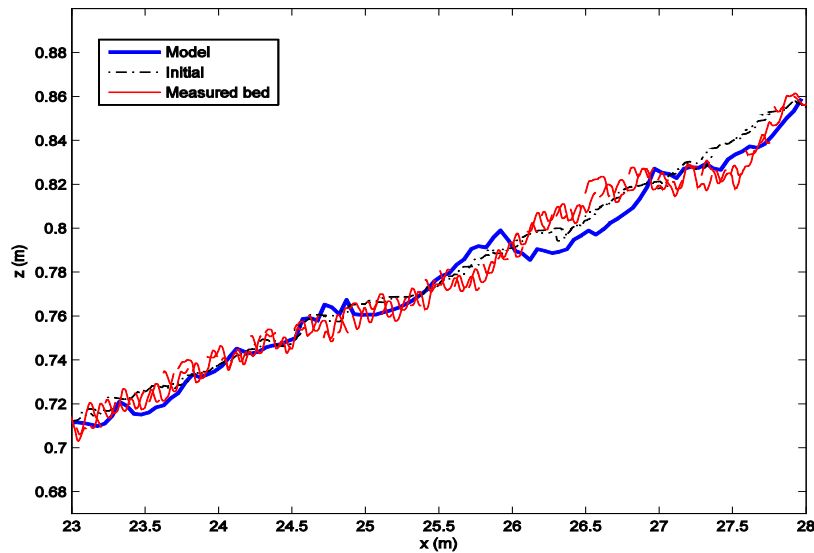


Figure 5 Calculated Beach profile at $t/T=50$ and measured beach profile for $H_s=0.2\text{m}$, $T_p=1.84\text{s}$, $h_{toe}=0.4\text{m}$

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