MODELLING BEACH TOPOGRAPHY EVOLUTION DUE TO WAVES AND CURRENTS IN THE VICINITY OF COASTAL STRUCTURES

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A numerical model of beach topography evolution due to waves and currents in the vicinity of coastal structures was developed. The model consists of five sub-models for nearshore random wave transformation, surface roller development, wave-induced currents, sediment transport, and morphological evolution. It was validated based on high-quality data sets from the Large-scale Sediment Transport Facility at the Coastal and Hydraulics Laboratory, in Vicksburg, Mississippi, USA. The simulations discussed here showed that the model well reproduced hydrodynamic conditions as well as beach morphological evolution in the vicinity of a detached breakwater. Previous simulations have confirmed the applicability of the model to simulate the conditions at other breakwater configurations and T-head groins.

INTRODUCTION

Coastal structures have been used since antiquity for reducing the shoaling in navigation channels and protecting harbors against wave action (Houston, 2003). Although there have been many debates about the advantages and disadvantages of coastal structures, they are still frequently utilized in coastal engineering projects to prevent beach erosion. Therefore, understanding the morphological evolution in the vicinity of coastal structures is necessary to achieve an optimal functional design. A number of numerical models have been developed and applied for simulating beach topography change around structures (e.g. Nicholson et al., 1997; Leont'yev, 1999; Zyserman and Johnson, 2002; Saied and Tsanis, 2005; Zyserman et al., 2005; Zanuttigh, 2007; Ding et al., 2006; Brøker et al., 2007). However, the nearshore hydrodynamics and sediment transport processes are highly complex in the vicinity of coastal structures. Thus, such models have only included a limited set of processes characterized by certain time and space scales. Moreover, the validation of numerical models is still limited because high-quality data sets from laboratories and fields are lacking. Therefore, the development of models that accurately predict the beach topographical evolution around structures remains a challenge.

The overall objective of this study is to develop a robust and reliable 2D horizontal numerical model of beach topography evolution due to waves and currents with the emphasis on the impact of coastal structures. In order to do this, a number of sub-models were developed, including (i) a random wave transformation model, (ii) a surface roller model, (iii) a wave-induced current model, (iv) a sediment transport model, and (v) a morphological evolution model. These sub-models were coupled and validated against a number of high-

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quality data sets from the Large-scale Sediment Transport Facility (LSTF) at the Coastal and Hydraulics Laboratory in Vicksburg, USA. In general, the predictions of beach morphological evolution in the vicinity of coastal structures by the numerical model were in good agreement with measurements.

MODEL DESCRIPTION

Nearshore Wave Transformation Model

The random wave transformation model was based on the energy balance equation with diffraction and dissipation terms (Mase, 2001; Nam et al., 2009; Nam and Larson, 2009, 2010; Nam, 2010; Nam et al., 2010; Nam et al., 2011). The energy dissipation term in the original EBED model (Mase, 2001) was modified based on the approach of Dally et al. (1985) to improve the prediction of wave conditions in the surf zone. Thus, the modified energy balance equation is expressed as follows,

$$\frac{\partial(v_x S)}{\partial x}+\frac{\partial(v_y S)}{\partial y}+\frac{\partial(v_\theta S)}{\partial \theta}$$
$$=\frac{\kappa}{2\omega}\left\{\left(CC_g\cos^2\theta S_y\right)_y-\frac{1}{2}CC_g\cos^2\theta S_{yy}\right\}-\frac{K}{h}C_g S\left\{1-\left(\frac{\Gamma h}{H_s}\right)^2\right\} \quad (1)$$

where S is the angle-frequency spectrum density, (x,y) the horizontal coordinates, (v_x, v_y, v_θ) the propagation velocities in their respective coordinate direction, θ the angle measured counterclockwise from the x axis, ω the frequency, C the phase speed, C_g the group speed, κ the free parameter that can be optimized to change the influence of the diffraction effects, h the still-water depth, K the dimensionless decay coefficient, and Γ the dimensionless stable coefficient.

Several previous studies have dealt with the empirical coefficients K and Γ. The values of these coefficients can be given by constants, e.g., $\Gamma = 0.4$ and $K = 0.15$ (Dally et al., 1985), or by empirical expressions containing the bottom slope (see Goda, 2006; Tajima and Madsen, 2006). In this study, a good description was obtained of the wave conditions in the surf zone for LSTF data by modifying the expressions for the coefficients proposed by Goda (2006) as follows,

$$\begin{cases}\Gamma = 0.45,\ K=\frac{3}{8}\left(0.3-19.2\,m\right) & : m<0\\ \Gamma = 0.45+1.5\,m,\ K=\frac{3}{8}\left(0.3-0.5\,m\right) & : 0\le m\le 0.6\end{cases} \quad (2)$$

where m is the bottom slope.

Surface Roller Model

The energy balance equation for the surface roller in two dimensions is expressed as (Dally and Brown, 1995; Larson and Kraus 2002),

$$P_D + \frac{\partial}{\partial x}\left(\frac{1}{2}MC_r^2 \cos^2 \overline{\theta}\right) + \frac{\partial}{\partial y}\left(\frac{1}{2}MC_r^2 \sin^2 \overline{\theta}\right) = g\beta_D M \quad (3)$$

where P_D is the wave energy dissipation ($= K\,C_g \rho g(H_{rms}^2 - (\Gamma h)^2)/(8h)$), M the period-averaged mass flux, C_r the roller speed ($\approx C$), and β_D the roller dissipation coefficient.

Nearshore Wave-induced Current Model

The governing equations for the nearshore wave-induced currents are written as,

$$\frac{\partial(h+\eta)}{\partial t} + \frac{\partial q_x}{\partial x} + \frac{\partial q_y}{\partial y} = 0 \quad (4)$$

$$\frac{\partial q_x}{\partial t} + \frac{\partial u q_x}{\partial x} + \frac{\partial v q_x}{\partial y} + g(h+\eta)\frac{\partial \eta}{\partial x} = \frac{\partial}{\partial x} D_x \frac{\partial q_x}{\partial x} + \frac{\partial}{\partial y} D_y \frac{\partial q_x}{\partial y} + f q_y - \tau_{bx} + \tau_{Sx} \quad (5)$$

$$\frac{\partial q_y}{\partial t} + \frac{\partial u q_y}{\partial x} + \frac{\partial v q_y}{\partial y} + g(h+\eta)\frac{\partial \eta}{\partial y} = \frac{\partial}{\partial x} D_x \frac{\partial q_y}{\partial x} + \frac{\partial}{\partial y} D_y \frac{\partial q_y}{\partial y} - f q_x - \tau_{by} + \tau_{Sy} \quad (6)$$

where η is the water level, (q_x, q_y) the flow per unit width in x and y direction, respectively, (u,v) the depth-averaged velocity, (D_x, D_y) the eddy viscosity coefficients, f the Coriolis parameter, (τ_{bx}, τ_{by}) the bottom stresses, and (τ_{Sx}, τ_{Sy}) the wave stresses.

The eddy viscosity in the offshore can be calculated from Falconer (1980), whereas it can be determined following Kraus and Larson (1991) for the surf zone. The bottom stresses can be calculated from Nishimura (1988). The wave stresses were derived by the wave transformation model and the surface roller model (for details see Nam et al., 2009; Nam and Larson, 2010; Nam, 2010). In the present study, the Coriolis force due to rotation of the earth is neglected. Thus, the value of Coriolis parameter *f* is set to 0.

Sediment Transport Model

In the swash zone, the net transport rates in the cross-shore and longshore directions can be calculated based on the study of Larson and Wamsley (2007) as,

$$q_{bc,net} = K_c \frac{\tan\phi_m}{\tan^2\phi_m - \left(dh/dx\right)^2} \frac{u_0^3}{g}\left(\frac{dh}{dx} - \tan\beta_e\right)\frac{t_0}{T} \quad (7)$$

$$q_{bl,net} = K_l \frac{\tan\phi_m}{\tan^2\phi_m - \left(dh/dx\right)^2} \frac{u_0^2 v_0}{g} \frac{t_0}{T} \tag{8}$$

where $q_{bc,net}$, $q_{bl,net}$ are the net transport in the cross-shore and longshore directions, respectively, K_c and K_l empirical coefficients, ϕ_m the friction angle for a moving grain ($\approx 30\,\text{deg}$), β_e the foreshore equilibrium slope, u_0, v_0 and t_0 the scaling velocities and time, respectively, and T the swash duration (assumed that T is equal to the incident wave period). The swash zone hydrodynamics without friction, which were derived based on the ballistic theory, were employed in the model (for details see Larson and Wamsley, 2007).

In the offshore and surf zone, the bedload can be calculated by the formula of Camenen and Larson (2005, 2007) as,

$$\frac{q_{bc}}{\sqrt{(s-1)gd_{50}^3}} = a_c \sqrt{\theta_c}\,\theta_{cw,m} \exp\left(-b_c \frac{\theta_{cr}}{\theta_{cw}}\right) \tag{9}$$

where the transport q_{bc} is obtained in the direction of the current (the transport normal to the current is taken to be zero), s the relative density between sediment and water, d_{50} the median grain size, a_c and b_c empirical coefficients, $\theta_{cw,m}$ and θ_{cw} the mean and maximum Shields parameters due to wave and current interaction, respectively, θ_{cr} the critical Shields parameter, and θ_c the Shields parameter due to current.

The suspended load in the surf zone and offshore zone can be derived from the advection-diffusion equation as,

$$\frac{\partial\left(\overline{C}d\right)}{\partial t} + \frac{\partial\left(\overline{C}q_x\right)}{\partial x} + \frac{\partial\left(\overline{C}q_y\right)}{\partial y} = \frac{\partial}{\partial x}\left(K_x d \frac{\partial\overline{C}}{\partial x}\right) + \frac{\partial}{\partial x}\left(K_y d \frac{\partial\overline{C}}{\partial y}\right) + \overline{P} - \overline{D} \tag{10}$$

where $\overline{C}$ is the depth-averaged sediment concentration, K_x and K_y the sediment diffusion coefficient in x and y direction, respectively, $\overline{P}$ the sediment pick-up rate, and $\overline{D}$ the sediment deposition rate (for details see Nam *et al.*, 2009).

Morphological Evolution Model

The beach morphological evolution under waves and currents was determined based on the sediment mass conservation equation as,

$$\frac{\partial h}{\partial t} = \frac{1}{1-n_p}\left(\frac{\partial q_{tot,x}}{\partial x} + \frac{\partial q_{tot,y}}{\partial y}\right) \tag{11}$$

where n_p is porosity parameter, and $q_{tot,x}$ and $q_{tot,y}$ the total load in x and y directions, respectively. In the swash zone, the total load is based on the net transport rates obtained by (7) and (8). In the offshore and surf zone, it is the sum of bed load and suspended load, which are calculated based on equations (9) and (10).

MODEL VALIDATION

Data Employed

Five series of physical model experiments were carried out in the basin of the LSTF (Gravens et al., 2006; Gravens and Wang, 2007; Hamilton and Ebersole, 2001; Wang et al., 2002) in order to obtain high-quality data sets for validating formulas for sediment transport, as well as investigating the beach evolution in the vicinity of detached breakwaters and T-head groins. The first series of experiments included four runs that were performed on a natural beach without structures. The second and third series of experiments, referred to as "Test 1" and "Test 2", were carried out with a detached breakwater in the basin that was located between profile Y22 and Y26, at four meter distance from the initial still water shoreline (see Fig. 1). Both Test 1 and Test 2 included eight runs approximately 190 min each. The fourth series, referred to as "Test 3", included six runs 180 min each, performed on a natural beach with a T-head groin. The last series of experiments, referred to as "Test 4", consisted of four runs 180 min each that were conducted in the basin with a detached breakwater. The breakwater length was shorter and its location was closer to the shoreline than for those in Test 1 and Test 2. The breakwater was located between profile Y27 and Y24, at 1.5 meter distance from the initial still water shoreline (see Fig. 1).

In all experimental runs, spilling breaking waves were generated by four wave-makers and the water was re-circulated by the pumping systems located up- and downstream of the basin. Wave gauges and acoustic doppler velocimeters were co-located at ten cross-shore positions on an instrument bridge. This bridge moved in the alongshore direction, thus the wave conditions and current velocities could be observed at specific cross-shore profiles. Three wave gauges (#11, #12, and #13) were located at three alongshore positions, 18.43 m seaward of the initial shoreline, to measure the wave conditions seaward of the toe of the movable beach. A rod and acoustic survey techniques were employed to measure the beach profiles after each experimental run. The beach in the basin consisted of well-sorted sand with a median grain size of 0.15 mm.

The numerical model has been validated against a number of data sets from LSTF basin (Nam and Larson, 2009 and 2010; Nam et al., 2010; Nam et al., 2011). In this study, two runs from Test 4 (T4C1 and T4C4) were employed to further validate the predictive capability of the model regarding nearshore waves, wave-induced currents, and morphological evolution for the detached breakwater experiment.

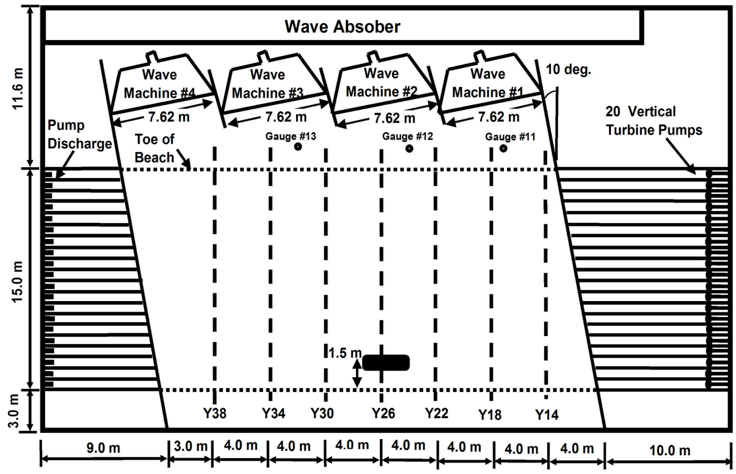

Figure 1. Configuration of LSTF basin for Test 4

Model Validation Against LSTF Data

The computational grid is generated based on the measured bathymetry from profile Y34 to Y14 with a grid cell size is 0.2 × 0.2 m. The wave spectrum density at the offshore boundary was calculated based on the wave conditions measured at three gages #11, #12, and #13 (see Table 1) and represented by a TMA spectrum with the parameter values γ=3.3, σ_a=0.07, σ_b=0.09, and the wave angular spreading S_{max}=25. The decay and stable wave height coefficient were determined from Eq. (2), and the roller dissipation coefficient was set to β_D=0.1. A Manning coefficient of 0.025 was employed to determine the bottom friction. The measured velocities at profile Y34 and Y14 were used to specify the influx and outflux of water at the lateral boundaries for the nearshore current model. At the offshore boundary, a radiation boundary condition was employed (Reid and Bodine, 1968). The values of K_c and K_l were both set to 0.0008 for calculating the net transport rates in the swash zone. The coefficient values a_c and b_c in the bedload formula were given as 12 and 4.5, respectively. The diffusion coefficients in the Eq. (12) were calculated based on the study of Elder (1959). The porosity parameter in the mass conservation equation was given as 0.4. For detailed information of the model input, see Nam et al., 2011.

Table 1. Offshore wave conditions for two selected test cases

Gages	Test case T4C1			Test case T4C4		
	H_{mo} (m)	T_p(s)	θ (deg.)	H_{mo} (m)	T_p(s)	θ (deg.)
# 11	0.220	1.448	6.5	0.221	1.452	6.5
# 12	0.223	1.481	6.5	0.223	1.483	6.5
# 13	0.224	1.466	6.5	0.225	1.469	6.5

The comparisons between calculated and measured significant wave height, longshore current, wave setup at Profile Y26 for T4C1 were presented in Fig. 2. In general, the numerical model reproduced the measurements satisfactorily. The calculation of significant wave height agreed very well with the measurements at all measured positions. The calculated longshore current was in good agreement at almost all measured positions, but underestimations were observed at two locations seaward of the breakwater (see Fig. 2b). The wave setup was also well reproduced by the model. Even though the model somewhat overestimated the setup at locations close to breakwater, the absolute difference between calculations and observations were relatively small.

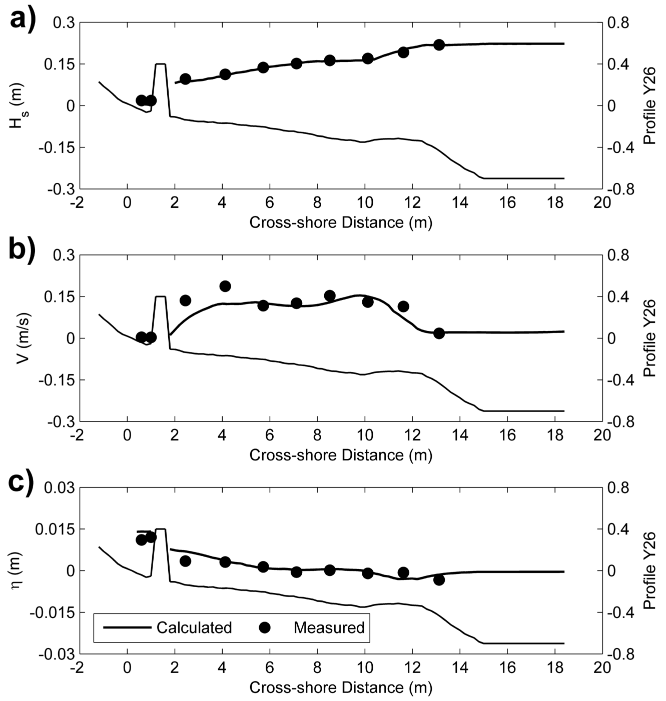

Figure 2. Comparisons between calculated and measured significant wave height (a), longshore current (b), and wave setup (c) for T4C1

Fig. 3 shows the comparison of calculated and measured bed levels for T4C1 after three hours. The dark lines represent the calculations, whereas the gray lines show the measurements. As can be seen, the beach morphological evolution was well predicted by the numerical model. The simulation showed that salient development in the lee of detached breakwater was in good agreement with the observed evolution. Although there were some discrepancies at the updrift side of the breakwater, the shoreline evolution reproduced the measurements well.

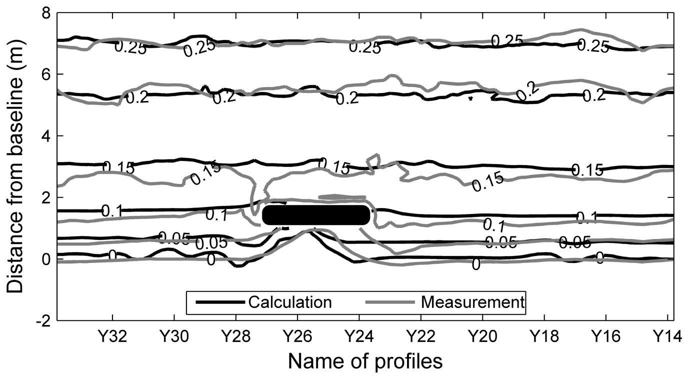

Figure 3. Comparison between calculated and measured bed levels after 3 hours for T4C1

As for T4C1, the computed significant wave height, longshore current, and wave setup at Profile Y26 for T4C4 were in good agreement with the measurements (see Fig. 4). As can be seen, the significant wave height was well reproduced by the numerical model. The calculated longshore current slightly underestimated measurements, whereas the predicted wave setup somewhat overestimated observations.

Fig. 5 illustrates the comparison between the calculated bed levels after three hours for T4C4. As for T4C1, the simulated beach topography in the vicinity of the detached breakwater was in good agreement with the measured, especially regarding the developed tombolo in the lee of the structure. The calculated shoreline positions were also well reproduced by the numerical model.

CONCLUSIONS

A generalized numerical model for predicting beach morphological evolution due to waves and currents in the vicinity of coastal structures was developed. The model was validated against high-quality data sets from experiments on the morphological impact of a detached breakwater in the LSTF basin, at Coastal and Hydraulics Laboratory, in Vicksburg, USA. The simulations showed that the hydrodynamic conditions, such as significant wave height, longshore current, wave setup, agreed well with measurements. The predicted beach morphological evolution was also satisfactory and in good agreement with observations.

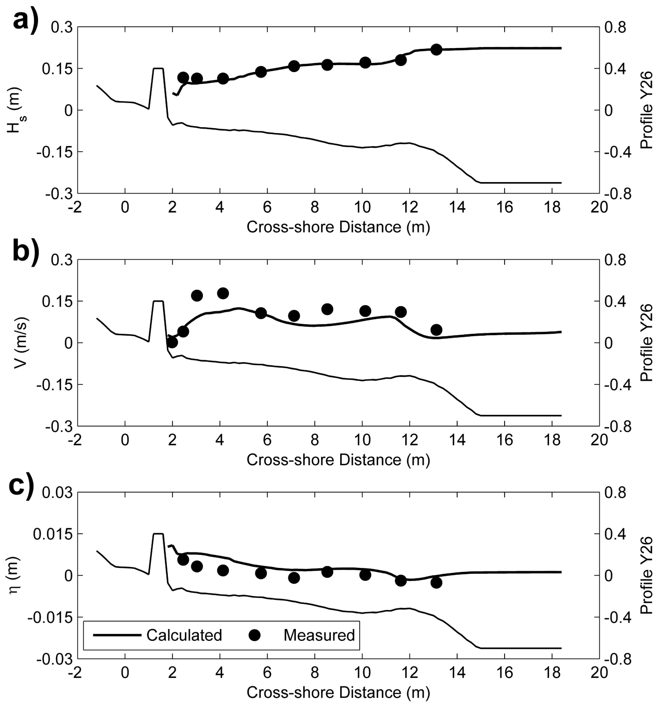

Figure 4. Comparisons between calculated and measured significant wave height (a), longshore current (b), and wave setup (c) for T4C4

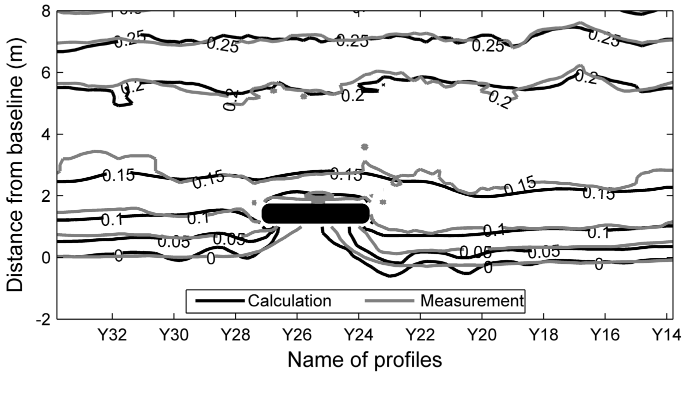

Figure 5. Comparison between calculated and measured bed levels after 3 hours for T4C4

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Breaking waves
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Surface roller
Wave-induced currents