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Numerical study on influences of breakwater layout on coastal waves, wave-induced currents, sediment transport and beach morphological evolution

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ABSTRACT

This study provides a numerical model to investigate the influences of breakwater layout on coastal waves, wave-induced currents, sediment transport and beach morphological evolution in the vicinity of breakwater. The numerical model is developed based on the sub-models for nearshore wave, wave-induced current, sediment transport and beach morphological evolution. Nearshore wave is simulated based on the parabolic mild-slope equation considering wave refraction, diffraction and breaking effects. Wave-induced nearshore current is modeled using the nonlinear shallow water equations in which wave radiation stresses are provided by wave model for driving current. Then, the two-dimensional suspended sediment transport equation, bed-load equation and coast beach morphological evolution are coupled with the wave and current models for simulating sediment transport and morphological evolution in coastal waves and wave-induced currents. The numerical model is firstly tested by the experiment results for coastal waves, near-shore currents, sediment transport and beach morphological evolution around breakwater from the Large-scale Sediment Transport Facility at the US Army Corps of Engineer Research and Development Center (Gravens and Wang, 2007). Then the model is used to study the influences of breakwater layout on coastal waves, wave-induced currents, sediment transport and beach morphological evolution by set several breakwater layouts in the LSTF basin.

1. Introduction

Scientific investigations of hydrodynamics along coast have demonstrated that wave flow system due to wave breaking has an indispensable effect on sediment transport and beach morphological evolution in coastal zones. Coast protection engineering works such as breakwaters can influence waves, wave-induced currents, deposition or erosion of sediment, and affecting local bathymetry and shoreline evolution. Coastal breakwater can effectively weaken the influence of waves for coastal shorelines, and moreover, it can reduce sediment transport and avoid local beach evolution and shoreline deposition and erosion largely. Understanding coastal waves, near-shore currents, sediment transport and beach morphological evolution in the vicinity of breakwaters is fundamental to the design of such coastal protection engineering works. To achieve the good protection for coastal beach and shoreline, different layouts of breakwater are always used in coastal protection projects. Thus, a study of the influences of breakwater layout on coastal waves, wave-induced currents and sediment transport is essential for analyzing coast erosion and deposition accurately and the layout optimization of such coastal protection engineering works.

There have been a lot of studies on numerical modeling of sediment transport and beach morphological evolution in coastal waves and currents, and different numerical and analytical models have been developed to predict coastal waves, near-shore currents, sediment transport and beach morphological evolution in the vicinity of breakwaters. Johnson et al. (1994) investigated the morphological response of a single detached breakwater subject to different wave conditions. Leont'yev (1999) proposed a coastal area model complex which concerned the treatment of the bottom drift and sediment transport in shoaling-breaking regions and swash zone to model the evolution of 2DH bottom topography during a given storm attacking a beach, both in its natural state and in the presence of structures. Zyserman and Johnson (2002) discussed the planform development (tombolo or salient) behind a single surface-piercing detached breakwater by a quasi-three-dimensional (Q3D) description which consisted of the flow, sediment transport and revised bed level update scheme. Lesser et al. (2004) simulated sediment transport and morphological devel-

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opment behind breakwater using the Delft3D model. Fernando and Pan (2005) developed a phase-resolving wave model accounting for wave refraction, diffraction and reflection and a quasi-3D sand transport model system which was predicated by a 1DV intra-wave-period numerical model based on the wave model. Artagan (2006) developed a numerical model based on one-line theory to evaluate the wind wave driven longshore sediment transport rate and shoreline change behind offshore breakwaters. Ding et al. (2006) integrated the phase-averaged wave model, the improved radiation stress formula, the cross-shore and longshore sediment transport rates and the morphodynamic changes of seabed model to simulate irregular wave deformations, wave-induced currents, sediment transport and morphodynamic changes around a detached breakwaters in coast. Li et al. (2007), based on the wave-current model of Fernando and Pan (2005), discussed implementation and validation of an intra-wave sand transport model around a breakwater in a prototype scale. Birben et al. (2007) studied the offshore protection process on the effect of offshore breakwater parameters (length, distance and gap), wave parameters (height, period and angle) and sediment accumulation ration. Du et al. (2010) applied the Coast2D model which was developed by the implementation of a wave overtopping module into an depth-averaged coastal morphological model to investigate the effect of wave overtopping on the hydrodynamics and morphodynamics around a group of shore-parallel breakwaters. Ranasinghe et al. (2010) used the Mike21 model to simulate nearshore currents (without morphological updating) due to waves acting on a single shore-parallel SBW located on a schematised beach with parallel depth contours. Nam et al. (2011) developed a numerical model for beach morphological evolution due to waves and currents in the vicinity of coastal structures, and the model includes five sub-models for random wave transformation, surface roller development, nearshore wave-induced currents, sediment transport and morphological evolution. Kristensen et al. (2013) present a new type of model that combined a process based area model, used to calculate sediment transport, with a simplified morphological updating scheme and the hybrid morphological model for calculating morphological changes induced by the presence of breakwaters. These researches have proposed various numerical models for predicting coastal sediment transport and beach morphological evolution due to coastal waves and currents. However, hydrodynamic and sediment transport processes are highly complex in nearshore zones, and presently there is no general model has been widely used in engineering studies for a wide range of conditions.

An accurate and efficient prediction of coastal waves is crucial for predicting near-shore current, and sediment transport and beach morphological evolution. In coastal zones, waves are usually in shallow water and undergo an obvious combined transformation of refraction and diffraction due to bathymetry, and the mild slope equation is an effective and efficient wave model for describing the variations of the wave amplitude of a wavelength. Compared to the wave energy models, the mild slope equation is capable of simulating both wave refraction and diffraction and is more economical for storage and computation compared to the phase-resolved models. However in previous study, near-shore current model, and sediment transport model and beach morphological evolution model have been usually implemented with wave phrase-resolve models or wave energy models, and the mild slope equation has less been used to implement with near-shore current model, and sediment transport model and beach morphological evolution model. Tang et al. (2016) provided an numerical model, in which the mild slope equation was used to implement with near-shore current model, and sediment transport model and beach morphological evolution model, for predicting sediment transport in coastal waves and wave-induced currents, and however the influence of breakwater on sediment transport and beach morphological evolution was not investigated. Besides, to achieve a good protection for coastal shorelines, different layouts of breakwater are always used in coastal protection projects. However the influences of breakwater layout on sediment transport and beach morphological evolution due to coastal waves and near-shore currents have been still less well studied.

This study provides a numerical model to investigate the influences of breakwater layout on coastal waves, wave-induced currents, sediment transport and beach morphological evolution in the vicinity of breakwater. The numerical model consists of the sub-models for nearshore wave transformation, wave-induced current, sediment transport and beach morphological evolution. Nearshore wave is simulated based on the parabolic mild-slope equation considering wave refraction, diffraction and breaking effects. Wave-induced nearshore current is modeled using the nonlinear shallow water equations in which wave radiation stresses are provided by wave model for driving current. Then, the two-dimensional suspended sediment transport equation, bed-load equation and coast beach morphological evolution are coupled with the wave and current models for simulating sediment transport and morphological evolution in coastal waves and wave-induced currents. The experimental results from the Large-scale Sediment Transport Facility (LSTF) at the US Army Corps of Engineer Research and Development Center in Vicksburg (Gravens and Wang, 2007) are used to validate the numerical model. Then the influences of breakwater layout on coastal waves, wave-induced currents, sediment transport and beach morphological evolution are studied by using the developed model. The rest of the paper is structured as follows. The numerical models are described in Section 2. In Section 3, the numerical models is firstly validated by the measured data to demonstrate its' validity and applicability, and then is used to study the influences of breakwater layout on waves, wave-induced currents, sediment transport and beach morphological evolution by changing the breakwater layout in LSTF experiment. Conclusions are presented in Section 4.

2. Numerical models

2.1. Nearshore wave transformation model

If waves propagate forward over coastal bathymetry in a main direction, and the reflection effects are ignored, the parabolic mild-slope equation can be effectively used to simulate wave transformation. Kirby (1986a) established an parabolic mild-slope equation based on a minimax principle for simulating wave propagation with a large incident angle, and the equation incorporating wave-breaking effect can be described as follows:

$$C_g\frac{\partial A}{\partial x}+\left(E'+\frac{1}{2}\frac{\partial C_g}{\partial x}\right)A-\frac{b_1}{\omega k}\frac{\partial^2}{\partial x\partial y}\left(CC_g\frac{\partial A}{\partial y}\right)+F'\frac{\partial}{\partial y}\left(CC_g\frac{\partial A}{\partial y}\right)=0 \tag{1}$$

in which

$$E'=\mathrm{i}(\bar{k}-a_0k)C_g+\frac{\mathrm{i}C_g}{2}D|A|^2+\frac{1}{2}\frac{D_b}{E} \tag{2}$$

$$F'=\frac{\mathrm{i}}{\omega}\left(a_1-b_1\frac{\bar{k}}{k}\right)+\frac{b_1}{\omega}\left(\frac{k_x}{k^2}+\frac{(C_g)_x}{2kC_g}\right) \tag{3}$$

$$D=k^3\frac{C}{C_g}\frac{(\cosh 4kh+8-2\tanh^2 kh)}{8\sinh^4 kh} \tag{4}$$

$$D_b=\frac{KC_g}{h}(E-E_S)=\frac{KC_g}{h}E\left(1-\left(\frac{\gamma_b h}{H}\right)^2\right) \tag{5}$$

where i is the imaginary unit, the positive direction of x is the wave propagation principal direction, y the direction perpendicular to x-axis, A complex wave amplitude, $C_g=\partial\omega/\partial k$ wave group velocity, $C=\omega/k$