



Modelling the effect of wave overtopping on nearshore hydrodynamics and morphodynamics around shore-parallel breakwaters

Yanliang Du^a, Shunqi Pan^{b,*}, Yongping Chen^b

^a China Institute of Water Resources and Hydropower Research, Beijing, 100038, China

^b School of Marine Science and Engineering, University of Plymouth, Drake Circus, Plymouth, PL4 8AA, United Kingdom

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ABSTRACT

Wave overtopping nearshore coastal structures, such as shore-parallel breakwaters, can significantly alter the current circulation and sediment transport patterns around the structures, which in turn affects the formation of tombolos and salients in the nearshore area. This paper describes the implementation of a wave overtopping module into an existing depth-averaged coastal morphological model: COAST2D and model applications to investigate the effect of wave overtopping on the hydrodynamics and morphodynamics around a group of shore-parallel breakwaters. The hydrodynamic aspects of the model were validated against a series of laboratory conditions. The model was then applied to a study site at Sea Palling, Norfolk, UK, where 9 shore-parallel segmented breakwaters including 4 surface-piercing and 5 low-crested breakwaters are present, for the storm conditions in Nov 2006. The model results were compared with laboratory data and field measurements, showing a good agreement on both hydrodynamics and morphological changes. Further analysis of wave overtopping effect on the nearshore hydrodynamics and morphodynamics reveals that wave overtopping has significant impacts on the nearshore circulation, sediment transport and the resulting morphological changes within such a complex breakwater scheme under the storm and macro-tide conditions. The results indicate the importance of including the wave overtopping in modelling nearshore morphodynamics with the presence of coastal structures.

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1. Introduction

Wave overtopping is a complex and important coastal process, commonly associated with the coastal defence structures. In the past decades, wave overtopping has been well studied with laboratory experiments and field measurements, focusing on safety and structural stability. The objectives of these studies have primarily been to determine the discharge of wave overtopping the nearshore structures and the results usually led to a set of empirical relationships between the environmental conditions, geometrical layout, material properties of the structure and the consequent overtopping discharge to be produced. For example, the experiments conducted by Owen (1980), van der Meer and Janssen (1995), van der Meer (2002), Schüttrumpf et al. (2002) and Hedges and Reis (1998, 2004), have all resulted in the formulae of wave overtopping discharge against sloped beaches and seawalls being derived for both laboratory and field conditions. However, these empirical formulae yield a wide range of overtopping discharge for the given conditions. The model of Hedges and Reis (2004) tends to predict lower overtopping rates in comparison with the exponential models of Owen and Steele

(1991) and van der Meer and Janssen (1995) for both low and high relative freeboards, but for the middle range freeboards, where the most experimental data are available, almost all models predict similar overtopping discharge rates. However, due to the parameters required, applying these empirical formulae to the complex field conditions has been rather difficult.

For the low-crested breakwaters, a series of recent work by Kramer et al. (2005), Lamberti et al. (2006, 2007), Calabrese et al. (2008), Zanuttigh and Martinelli (2008) and Zanuttigh et al. (2008) aims to provide an integrated empirical formula for wave transmission and wave overtopping discharge and infiltration through the porous breakwaters based on a number of large scale laboratory experiments, which can be adopted in process models. Further study by Vicinanza et al. (2009) on the experimental data of Cáceres et al. (2008) yielded simple and practical methods for predicting the wave height around the breakwaters.

In addition to the experimental studies, helped by the rapid development in computing power and numerical methods, numerical models have been developed to compute wave run-up, transmission and overtopping, as feasible and practical tools (Hu et al., 2000; Hubbard and Dodd, 2002; Xiao et al., 2009). These studies are often limited to one-dimensional cases with emphasis on the intra-wave period hydrodynamics induced by wave overtopping along cross-shore profiles. In nearshore areas where coastal defence structures are

* Corresponding author. Tel.: +44 1752 586 140; fax: +44 1752 586 101.
E-mail address: shunqi.pan@plymouth.ac.uk (S. Pan).

present, the hydrodynamics and morphodynamics affected by wave overtopping become considerably more complicated. Although the morphological responses and beach changes around nearshore structures can be studied using physical models, see Dally and Pope (1986), Herbrich (1989), Whitehouse (1998) and Sumer et al. (2001), and numerical models, see de Vriend et al. (1993), O'Connor et al. (1995), Nicholson et al. (1997), and Zyserman and Johnson (2002), the effect of wave overtopping structures on the nearshore hydrodynamics and morphodynamics has been rarely included in these studies, despite the wide recognition of its importance for coastal morphological evolution under short-term storm conditions and in the long-term. The recent work of Cáceres et al. (2005) intended to address this aspect by including the impact of wave overtopping on nearshore morphodynamics in a Q3D model in studying the sensitivity of the functional design of structures, but the work lacked of detailed comparisons with the measurements.

Recently, a research project – LEACOST2 was funded by the UK Engineering and Physical Sciences Research Council (EPSRC), to study the impact of the shore-parallel breakwaters at Sea Palling (Norfolk, UK) on the adjacent beaches and coasts for improving the existing design guidelines for such structures, Pan et al. (2007, 2008). As part of the project, a process-based coastal hydrodynamic and morphodynamic computer model – COAST2D was further developed to include the effect of wave overtopping on the nearshore circulation and morphological changes, supported by the large scale field measurements carried out within the project. Whilst the details of the LEACOST2 project can be found elsewhere (<http://www.research.plym.ac.uk/cerg/leacost2/>), this paper will focus on the aspects of implementation, validation and application of the wave overtopping module as an important element of further development of the existing COAST2D model. The wave overtopping module uses the empirical formulae suggested by Hedges and Reis (2004) for computing wave overtopping discharge, and is dynamically coupled with the hydrodynamic and morphodynamic computations from COAST2D to account for the time-varying wave and tide conditions. The integrated model is first validated using the laboratory experimental data from an EU funded project (Cáceres et al., 2008) and followed by applications to the LEACOST2 project site at Sea Palling to study the impacts of wave overtopping on the nearshore circulation and the consequent sediment transport and resulting bed level changes for the storm events in November 2006. The paper will briefly describe the COAST2D model, including the principal governing equations, but focus on the details of implementing wave overtopping module, followed by the model validation against the laboratory data. Finally, the results of the model applications to the Sea Palling site are presented and discussed in detail.

2. Model description

The existing COAST2D model is a two dimensional depth-integrated, wave phase-averaged and fully coupled coastal hydrodynamic and morphological model, see Pan et al. (2005). The model mainly consists of the hydrodynamic and morphodynamic modules. The hydrodynamic modules compute waves and currents (induced by both waves and tides), taking account for wave refraction/diffraction, wave breaking, tides, turbulence, bedform-enhanced bottom friction and wave-current interactions. The morphodynamic modules compute the sediment transport rates under the combined wave and current conditions using the equilibrium sediment transport approaches, and the resulting bed level changes. Spatial variation of sediment size (sediment map) can also be included in the model. During the LEACOST2 project, an additional module to include the wave overtopping effect has been implemented and integrated into the COAST2D model. For the sake of the completeness, the principal governing equations for currents, waves and sediment transport used in COAST2D are given below, along with the details of implementation of the wave overtopping module.

2.1. Currents

The governing equations for the depth-integrated currents are given as:

$$\frac{\partial z}{\partial t} + \frac{\partial}{\partial x_i}(dU_i) = S \quad (1)$$

$$\frac{\partial U_i}{\partial t} + U_j \frac{\partial U_i}{\partial x_j} + g \frac{\partial z}{\partial x_i} = \frac{\partial}{\partial x_j} \left(\nu_t \frac{\partial U_i}{\partial x_j} \right) - \frac{1}{\rho d} \frac{\partial S_{ij}}{\partial x_j} + \frac{\tau_{si}}{\rho d} - \frac{\tau_{bi}}{\rho d} + f_i \quad (2)$$

where $i, j = \{1, 2\}$ are indices of horizontal directions in Cartesian coordinates, t is time, z is water surface elevation, d is water depth, U_i is depth-mean current velocity vectors, S is source/sink term to include wave overtopping discharge, g is gravity acceleration, ρ is density of water, S_{ij} are wave radiation stresses, ν_t is eddy viscosity, τ_b is bottom shear stress, τ_s is surface shear stress due to the wind, and f is Coriolis force.

2.2. Waves

The governing equations for the period-averaged wave energy (amplitude) and directions are described as (Phillips, 1977):

$$\frac{\partial A}{\partial t} + \frac{1}{2A} \frac{\partial}{\partial x_i} \left\{ A^2 \left(\frac{C_g}{k} K_i + U_i \right) \right\} + \frac{S_{ij}}{\rho g A} \frac{\partial U_j}{\partial x_i} + C_a A = 0 \quad (3)$$

$$\frac{\partial K_i}{\partial t} + \left[C_g \frac{K_j}{k} + U_j \right] \frac{\partial K_i}{\partial x_i} + \frac{\sigma G}{2d} \frac{\partial d}{\partial x_i} - \frac{C_g}{2k} \frac{\partial \Phi}{\partial x_i} + K_j \frac{\partial U_j}{\partial x_i} = 0 \quad (4)$$

where A is wave amplitude, K_i are wave number vectors, k is wave separation factor, C_g is wave group velocity, C_a is coefficient for wave energy dissipation due to bottom friction and wave breaking, $G = 2kd/\sinh(2kd)$, σ is intrinsic wave frequency, and Φ is a term related to wave diffraction ($\Phi = \frac{1}{A} \nabla^2 A$).

2.3. Wave overtopping

The implementation of the new wave overtopping module in the present study is primarily focused on the estimation of the phase-averaged wave overtopping discharge at the nearshore structures. This study uses shore-parallel breakwaters as an application, but the approach is also applicable to other forms of coastal defence structures such as seawalls. The key element of the implementation is to determine the wave overtopping discharge based on the wave and tide conditions produced by the hydrodynamic modules in the COAST2D model, so that continuous spatial and temporal variation of the wave and tide conditions can be taken into account. In general, the phase-averaged wave overtopping discharge per unit width of the structure, Q_{ovt} , is a function of many factors related to the geometry of the structure and the wave conditions (significant wave height, wave period and wave attack angle) at the toe of the structure, the height of the freeboard, the front slope and roughness of the structure, and water depth. Following a review of all the available models for calculating wave overtopping discharge, the overtopping model of Hedges and Reis (1998) was selected as the most appropriate for implementation. This wave overtopping model is extended from the overtopping theory for regular waves developed by Kikkawa et al. (1968) for random waves and assumes that the front of the breakwater can be treated as a weir-type seawall. The wave overtopping discharge can be estimated with the following equations:

$$\frac{Q_{ovt}}{\sqrt{gH_s^3}} = \begin{cases} A_1 \left(\frac{R_{max}}{H_s} \right)^{3/2} \left(1 - \frac{1}{\gamma_r} \frac{R_c/H_s}{R_{max}/H_s} \right)^{B_1} & 0 \leq \frac{R_c/\gamma_r}{R_{max}} < 1 \\ 0 & \frac{R_c/\gamma_r}{R_{max}} \geq 1 \end{cases} \quad (5)$$

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