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Numerical simulation of wave overtopping at coastal dikes and low-crested structures by means of a shock-capturing Boussinesq model

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ABSTRACT

In this paper, a shock-capturing numerical model, based on the combined solution of Boussinesq and nonlinear shallow water equations is applied to the simulation of wave runup, overtopping and wave train propagation over impermeable, emerged and low-crested, structures. In order to improve the performances of the scheme at wet–dry interfaces, a numerical treatment is introduced to provide well-balancing of advective fluxes and source terms. One- and two-dimensional test cases are presented to validate the performances of the model under both regular and irregular wave conditions.

1. Introduction

Wave overtopping is an important parameter in the design of several types of coastal structures. A reliable prediction of overtopping discharges is necessary to determine the crest height and width of new sea dikes, levees and breakwaters built to defend inland areas from flooding. It is also important to assess the risk of inundation at existing coastal defence structures, a topical problem in the light of the ongoing sea level rise. Wave overtopping is also relevant in the design of low-crested structures, which are frequently constructed to protect shores from coastal erosion. In fact, wave overtopping influences the circulation patterns that develop around such structures, conditioning their morphological impact on the adjacent littoral (Vicinanza et al., 2009; Zanuttigh et al., 2008).

In the past ten years, wave overtopping was investigated in a large number of studies and projects, mostly of experimental nature (e.g. De Rouck et al., 2001; Van der Meer et al., 2009), which led to the development of several empirical prediction formulae (CEM, 2003; EurOtop Manual, 2007; TAW, 2002). The validity of such formulae is restricted to specific wave conditions and structural characteristics, as it is constrained to the configurations tested in the laboratory. This restriction affects the prediction of wave overtopping at low-crested structures, because traditionally only well-emerged defence structures were studied; thus, most of the available relations are not accurate for small freeboards. Moreover, most empirical relations estimate mean discharge rates but do not provide information on the entity or duration of individual events, which are important when considering the impacts of flooding on defended areas or the resistance of a structure to the overtopping flow. A limited number of studies was dedicated to investigating and predicting wave by wave overtopping characteristics, like maximum discharge values or flow velocities (Schüttrumpf, 2001; Van der Meer and Janssen, 1995; Van Gent, 2002; Victor et al., 2012). In the situations where the applicability of empirical or semi-empirical formulae is uncertain, numerical modelling can be a useful support to the design of coastal structures.

In order to provide a realistic and reliable prediction of wave overtopping, a numerical model should be able to simulate wave transformation from deeper to shallow water, wave breaking, wave runup on the structure and the possible flow of water over and beyond it. The last two requirements demand the capability to accurately model the process of wetting and drying. Numerical models which solve the nonlinear shallow water equations (NSWEs) by means of shock-capturing techniques possess such a capability and have been frequently applied to simulate wave overtopping (e.g. Dodd, 1998; Hu et al., 2000; Tuan and Oumeraci, 2010). The drawback of these models lies in the need to assign wave conditions close to the structure, due to the impossibility of reproducing wave propagation employing the NSWEs, which neglect the effects of frequency dispersion. On the other hand, Boussinesq-type models, which incorporate nonlinear and dispersive properties, are suitable to simulate wave propagation but are rarely employed when overtopping phenomena must be taken into account. This shortage may be ascribed to the difficulty of treating wetting and drying within the framework of traditional Boussinesq models, which require artificial and often complex algorithms to deal with moving shorelines (e.g. Lynett et al., 2002; Madsen et al., 1997; Zelt, 1991). Recently, numerical models based on the Reynolds averaged Navier–Stokes equations (RANS) have

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received an increasing amount of attention in the context of overtopping simulations (e.g. Ingram et al., 2009; Losada et al., 2008; Reeve et al., 2008), given their ability to provide detailed information on the flow characteristics as waves interact with structures. Their applicability is however still limited by a significant computational cost, especially when two horizontal dimensions are considered. Therefore, the application of simplified but efficient schemes is still attractive.

In this work, a shock-capturing model recently validated for the simulation of regular and irregular wave breaking (Tonelli and Petti, 2009, 2012) is proposed for wave overtopping simulations. The numerical model is based on the joint solution of Boussinesq and NSW equations. The rationale behind the model consists in combining the best features of the two families of equations, exploiting the complementarity of their applicability domains. As anticipated, Boussinesq-type equations (Kirby, 2003; Madsen and Schäffer, 1999 for a review) take into account both the nonlinear and the frequency-dispersive features of wave motion, well representing wave propagation, but they are not suited to model wave breaking, swash motion and wave overtopping. Such processes are characterized by the prevailing of nonlinearity over frequency dispersion, thus they can be studied efficiently by means of the NSWEs, which are a non-dispersive subset of Boussinesq-type equations. Keeping this in mind, the proposed model solves a set of Boussinesq-type equations where nonlinear and dispersive effects are both relevant and the NSWEs where dispersion is negligible with respect to nonlinearity. The scheme is based on the finite volume method to benefit from the shock-capturing features of the NSWEs. Therefore, once NSWEs are applied, flow discontinuities, such as propagation on a dry bed, bore evolution and the related energy loss, emerge as parts of the solution. As a result, the numerical model can reproduce the propagation and transformation of broken waves, at least of spilling type, and it can intrinsically capture shoreline motion, which are all important aspects for the simulation of overtopping phenomena.

Given these features, the numerical model is expected to effectively represent wave overtopping at coastal dikes and sloping seawalls, predicting both averaged discharge values and wave by wave flow characteristics. On the other hand, the simplifications of the governing equations and the Eulerian nature of the solution technique, make the numerical model unsuitable for the simulation of violent overtopping events at vertical or very steep seawalls, which are characterized by impulsive impacts with the formation of splashes and spray. Therefore, this second type of overtopping scenarios will not be considered here.

With respect to the scheme presented in Tonelli and Petti (2012), the numerical treatment of wet–dry transitions was modified to ensure well-balancing of the scheme also in the presence of emerging topographies, following the works of Audusse et al. (2004), Liang and Marche (2009) and Liang (2010). Similar techniques were recently proposed by Kazolea and Delis (2013), Orszaghova et al. (2012) and Roeber and Cheung (2012) in their Boussinesq–NSWE models.

The paper is structured as follows: the numerical model is described in Section 2 — the governing equations are presented and the numerical scheme is outlined, focusing the attention on the modified treatment of wetting and drying. The test cases are reported in Section 3. The model is first applied to reproduce solitary wave evolution over initially dry and submerged reefs in order to verify its ability to capture the propagation of moving wave fronts. Then, regular and irregular wave overtopping of emerged structures is simulated in one-dimensional conditions. Finally, a two-dimensional test case is proposed: the model is applied to study the effect of wave overtopping on the hydrodynamic circulation around a low-crested structure. Even if wave overtopping is not particularly violent in such conditions, its influence on the wave-current field, and hence on the evolution of the protected littoral, is important and should be carefully taken into account.

2. Numerical model

2.1. Governing equations

The numerical scheme solves the 2DH extended Boussinesq equations derived by Madsen and Sørensen (1992) for slowly varying bathymetries formulated in conservative form as:

$$\begin{bmatrix} h \\ P \\ Q \end{bmatrix}_t + \begin{bmatrix} P \\ P^2/h + gh^2/2 \\ PQ/h \end{bmatrix}_x + \begin{bmatrix} Q \\ PQ/h \\ Q^2/h + gh^2/2 \end{bmatrix}_y + \begin{bmatrix} 0 \\ -ghz_x + \psi_1 + \tau_1/\rho \\ -ghz_y + \psi_2 + \tau_2/\rho \end{bmatrix} \tag{1}$$

where h is the total water depth, P and Q are the volume fluxes along the directions x and y, g is the gravitational acceleration and ρ is the fluid density. The symbols ψ_1 and ψ_2 denote the modified dispersive terms given by

$$\begin{aligned} \psi_1 = & -\left(B + \frac{1}{3}\right) d^2 \left(P_{xxt} + Q_{xyt}\right) - Bgd^3 \left(\eta_{xxx} + \eta_{xyy}\right) \\ & - dd_x \left(\frac{1}{3} P_{xt} + \frac{1}{6} Q_{yt} + 2Bgd\eta_{xx} + Bgd\eta_{yy}\right) - dd_y \left(\frac{1}{6} Q_{xt} + Bgd\eta_{xy}\right) \\ \psi_2 = & -\left(B + \frac{1}{3}\right) d^2 \left(P_{xyt} + Q_{yyt}\right) - Bgd^3 \left(\eta_{yyy} + \eta_{xxy}\right) \\ & - dd_y \left(\frac{1}{3} Q_{yt} + \frac{1}{6} P_{xt} + 2Bgd\eta_{yy} + Bgd\eta_{xx}\right) - dd_x \left(\frac{1}{6} P_{yt} + Bgd\eta_{xy}\right) \end{aligned} \tag{2}$$

with d standing for the still water depth and η for the water surface elevation measured from the still water level. B is a calibration coefficient which determines the dispersion properties of the equations; the value $B = 1/15$ was adopted, as suggested by Madsen and Sørensen (1992).

The terms τ_1 and τ_2 represent bottom friction and are approximated by Manning's friction law:

$$\begin{bmatrix} \tau_1/\rho \\ \tau_2/\rho \end{bmatrix} = gn^2 \frac{\sqrt{U^2 + V^2}}{h^{1/3}} \begin{bmatrix} U \\ V \end{bmatrix} \tag{3}$$

where n is Manning's coefficient and the symbols U and V denote the depth-averaged velocities along the directions x and y. By using this expression it is implicitly admitted that the flow is fully turbulent, which is a reasonable assumption for the conditions considered in the following.

It is important to note that when the dispersive terms in (1) are neglected, the nonlinear shallow water equations are recovered

$$\begin{bmatrix} h \\ P \\ Q \end{bmatrix}_t + \begin{bmatrix} P \\ P^2/h + gh^2/2 \\ PQ/h \end{bmatrix}_x + \begin{bmatrix} Q \\ PQ/h \\ Q^2/h + gh^2/2 \end{bmatrix}_y + \begin{bmatrix} 0 \\ -ghz_x + \tau_1/\rho \\ -ghz_y + \tau_2/\rho \end{bmatrix} = 0. \tag{4}$$

2.2. Numerical scheme

The finite volume method (FVM) has been adopted to take advantage of the shock-capturing abilities of the NSWEs. Such method cannot be applied to the equations (1) straightforwardly, due to the presence of high-order derivatives in the dispersive terms (2); therefore, following Erduran et al. (2005), a hybrid technique is adopted. The advective part of the equations is solved explicitly, employing the FVM; whereas dispersive and bottom slope terms are treated as source terms and discretized