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Numerical analysis of wave overtopping of rubble mound breakwaters

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Abstract

The paper describes the results of a two-dimensional (2-D) numerical modelling investigation of the functionality of rubble mound breakwaters with special attention focused on wave overtopping processes. The model, COBRAS-UC, is a new version of the COBRAS (Cornell Breaking Waves and Structures) based on the Volume Averaged Reynolds Average Navier–Stokes (VARANS) equations and uses a Volume of Fluid Technique (VOF) method to capture the free surface. The nature of the model equations and solving technique provides a means to simulate wave reflection, run-up, wave breaking on the slope, transmission through rubble mounds, overtopping and agitation at the protected side due to the combined effect of wave transmission and overtopping. Also, two-dimensional experimental studies are carried out to investigate the performance of the model. The computations of the free surface and pressure time series and spectra under regular and irregular waves, are compared with the experimental data reaching a very good agreement. The model is also used to reproduce instantaneous and average wave overtopping discharge. Comparisons with existing semi-empirical formulae and experimental data show a very good performance. The present model is expected to become in the near future an excellent tool for practical applications.

Keywords: Rubble-mound breakwater; RANS modelling; Wave transformation; Overtopping; Functional design; Numerical modelling

1. Introduction

Wave overtopping of coastal structures is one of the most relevant processes taking part in the complex water wave and structure interaction phenomenon. Once the highest run-up levels exceed the structure crown, overtopping occurs, which may cause structural failure, damage to harbor infrastructures, properties and lives. Research on wave overtopping has been of great interest during the last decades. Very important developments have been achieved during the last years thanks to several European projects (f.i. CLASH and VOWS). The prediction of wave overtopping is especially challenging since it involves complicated processes such as wave run-up on permeable or impermeable slopes, wave breaking and associated turbulence; wave infiltration and transmission in rubble mound layers or violent impacts on monolithic walls. In general, most of the existing research has been directed towards the evaluation of the mean overtopping discharge. However, this may not be the fundamental parameter. Therefore, further efforts have been oriented towards the evaluation of other important parameters such as the volume of the maximum individual overtopping event or overtopping probability. Furthermore, the thickness of the overtopping layer and the associated flow velocity; the evaluation of forces on the structure during an overtopping event; the forces induced on infrastructures, vehicles or people on the crown of the structure or the transmission leeward the structure induced by overtopping events are also of great interest. The main problem is that overtopping depends on structure typology, geometry, material characteristics, incident wave conditions and foreshore bathymetry requiring a strong parameterization to include all the relevant elements.

In order to provide design guidelines for coastal structures, many semi-empirical formulations based on flume and basin experiments have been developed in the past. Such formulae try to consider and parameterize the most relevant variables ruling the process. Most of them are simple expressions describing mean overtopping discharges and are biased towards sloping or vertical seawalls, for example Owen (1980), Van der

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Meer and Janssen (1995), Hedges and Reis (1998) and Besley (1999). Formulae for rubble mound structures are also available in literature, Franco et al. (1994) and Franco and Franco (1999), Allsop et al. (1985), later improved by Besley (1999), and Pedersen (1996).

Some efforts have focused on the empirical prediction of the volume of maximum overtopping events, Owen (1980) and Franco et al. (1994) as an important criterion for design. Most of the formulae are summarized in Burcharth and Hughes (2006) and will be included in the forthcoming "European Wave Overtopping Manual".

These empirical formulations have been the main tool for coastal structure design and have proved to be successful. However, they are based on flume or wave basin experiments covering a limited number of typologies and setups. Furthermore, many of them are based on a reduced set of incident wave conditions including mostly regular waves or narrow-banded spectra. Their use out of range, a problem often faced for design, may require extrapolations increasing uncertainties, and/or lead to important errors. To overcome these limitations, computational modeling of wave interaction with coastal structures has grown as a serious complementary approach during the last decade, Losada (2003).

Numerical model performance for wave and structure interaction including wave overtopping, depends on the equations and solving technique, and relies heavily on a thorough validation process. The most popular models are based on different forms of the nonlinear shallow water equations (NSWE), f.e. Kobayashi and Wurjanto (1989a,b), Mingham and Causon (1998), Hu et al. (2000), Hubbard and Dodd (2002), Stansby and Feng (2004). The NSWE are derived on the assumption of hydrostatic pressure and are obtained by vertically integrating the Navier–Stokes equations. Models based on these equations are very efficient, providing the chance to simulate wave trains including about 1000 waves very rapidly, which may be of importance to analyze extreme statistics of wave overtopping. However, the use of NSWE places severe restrictions to real applications inherent to the hypothesis behind their derivation. One restriction is that the offshore boundary condition of the numerical model has to be located close to the structure in order to satisfy the shallow water limit. This restriction is especially crude when considering high frequency components in the incident wave spectrum. This may lead to important errors in the estimation of wave overtopping. Additional restrictions are associated with the semi-empirical introduction of breaking, porous flow modeling or the difficulty in simulating complicated free surfaces.

A second and more recent alternative is the use of particle methods like the Moving Particle Semi-Implicit (MPS) method of Koshizuka et al. (1995); or the Smoothed Particle Hydrodynamics (SPH) method in its different versions (f.e. Dalrymple et al. (2001), Gotoh et al. (2004) and Shao et al. (2006)). The main advantage of these models, being a grid-less Lagrangian approach, is that they provide excellent capability to track large deformations of the free surface with good accuracy. However, SPH models are, at the moment, only applicable to impermeable structures and have a clear disadvantage compared to other models, their extremely low computational efficiency. As a consequence, limited validation but promising initial results are currently available (i.e. Shao et al., 2006).

A third alternative is the numerical model based on the Navier–Stokes equations. The main advantage of these models is that they overcome the limitations associated with using a given wave theory and include wave breaking thanks to incorporating a turbulence model and considering Reynolds Average (RANS) equations. Those including a Volume of Fluid technique to track the free surface are becoming very powerful since they are able to consider large free surface deformations. Moreover, they are computationally more efficient than the SPH models. Several researchers have been working on this type of models (f.e.: Troch and de Rouck, 1998; Kawasaki, 1999; Li et al., 2004a,b).

Liu et al. (1999) presented a RANS model; nicknamed COBRAS (Cornell Breaking Waves and Structures) to simulate breaking waves overtopping a porous structure. The model calculated the mean flow in the fluid region based on the Reynolds averaged Navier–Stokes equations, the corresponding turbulence field being modelled by an improved k–ε model. The flow in porous structures was described by the spatially averaged Navier–Stokes equations. However, due to model and computational limitations, the model was validated for a vertical caisson protected by an armoured layer made of tetrapods in a very small computational domain (7.348 m × 0.43 m) and for a very short simulation time (t = 18.2 s) and therefore for a limited number of regular waves (13).

In a second paper Hsu et al. (2002) extended the original COBRAS model, introducing the Volume-Averaged/Reynolds Averaged Navier–Stokes (VARANS) equations to describe surface wave interaction with coastal structures. In the VARANS equations, the volume-averaged Reynolds stress is modelled by adopting the nonlinear eddy viscosity assumption and the volume-averaged turbulent kinetic energy and its dissipation rate are derived by taking the volume-average of the standard k–ε equations. This model has the advantage of introducing the small-scale turbulence effects as part of the porous flow. Validation is carried out using the experimental set in Liu et al. (1999) and is also for a very small domain and limited simulation time. In this case, most of the validation focuses on the regular wave field in front of the structure.

In this paper an improved version of COBRAS, COBRAS-UC, developed at the University of Cantabria is used to investigate the interaction of random waves with rubble mound breakwaters focusing on the complicated overtopping process. The model is used to simulate a large numerical wave flume including random waves and long simulation times, which may contribute to reduce some uncertainties in using semi-empirical formulae for design and provide some statistical information on the overtopping process.

The paper is organized in the following manner. The main modifications introduced in the initial COBRAS version are presented in the following section. Section 3 describes the physical model experimental work carried out for model validation, including free surface, pressure and wave overtopping measurements in a rubble mound breakwater under regular and irregular