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Numerical modelling of armour block sea breakwater with smoothed particle hydrodynamics

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ABSTRACT

The application of smoothed particle hydrodynamics (SPH) to model the three-dimensional fluid–structure interaction for waves approaching a rubble mound breakwater is presented. The main aim is to model the armoured structure and to validate its response under the action of periodic waves. The complex geometry is represented by grooved cubic blocks such that the surrounding gaps within the breakwater seaward layer require a large number of particles to obtain a sufficiently detailed description of the flow. Using novel computer architecture solutions such as graphics processing units (GPUs), the fluid-structure interaction is modelled with SPH particles between armour blocks that are representative of the real structure. The open-source GPU code, DualSPHysics, enables the simulation of millions of particles required for the accurate simulation of the run-up on an armoured structure. SPH has been proven to be a suitable method for practical applications in coastal engineering. In the present work the run-up heights are computed and compared with empirical solutions and experimental data. Reasonable agreement is obtained for the run-up due to regular waves over a range of surf similarity numbers from 3.0 to 5.5.

1. Introduction

Coastal defences are built to protect the population and infrastructure in coastal zones. These structures defend not only houses, seafronts, beaches, recreational areas, but also harbours and ports where the maritime shipping plays a key role in the world economy. These defences protect infrastructures against storm surge and large waves that may cause run-up and overtopping on structures such as breakwaters, dikes, seawalls, etc., leading to potential damage and flooding of the area behind the structure.

In particular, this work is focused on the numerical simulation of breakwaters such as those shown in Fig. 1. The study and analysis of the better design of a breakwater can be modelled physically in laboratory facilities or computationally using a numerical model. Many examples can be found in the literature [1–4] examining the optimization and design of different breakwaters.

The wave run-up height is a key parameter in design of such kind of coastal structures to define the breakwater crest height [5]. The resilience of these structures against the waves can be represented by means of the slope equivalent roughness coefficient [6,7]. This coefficient depends on the armour units layout, shape and size, and hence the porosity of the seaward layers. An appropriate value of roughness based on detailed experimental and numerical validation can lead to an efficient design of a structure with proper values of overtopping flows and run-up heights.

Within the European research project CLASH (Crest Level Assessment of coastal Structures by full-scale monitoring, neural network prediction and Hazard analysis on permissible wave overtopping, www.clash-eu.org), field measurements were carried out at various locations worldwide along with laboratory tests. One of the main goals of the CLASH project was the creation of a large database containing more than 10,000 test results on wave overtopping to develop a generic prediction method for overtopping at coastal structures. One of these locations in Europe with complete series of field and laboratory measurements is a rubble mound breakwater armoured with antifer blocks at Zeebrugge, Belgium. A further objective of the CLASH project also focused on investigating physical scale and model effects for run-up and wave overtopping. The Zeebrugge breakwater will be used herein as reference to validate the numerical results.

Modelling the armour block sea defences involves two scales: the treatment of the bulk properties of the slope and the modelling of the interstitial fluid-structure interaction, which resembles flow through a permeable medium. The porosity of the armoured layer

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Fig. 1. Pictures of the antifers breakwater in Molfetta (Italy) and rubble mound breakwater in Muxía (Spain).

must be reproduced to allow the fluid to flow between the blocks and dissipate its energy reducing the run-up process.

The difficulty to simulate breakwaters using numerical schemes comes from the complex geometries and the violent hydrodynamics involved in the process. Traditionally, the design is based on empirical relations and physical model results. However, numerical modelling presents some advantages in comparison to physical experiments such as the cost in time, resources and money. Numerical models provide information that is either hard to measure or near impossible to obtain from physical experiments. Some Eulerian numerical methods have been applied in the design of breakwater such as volume-of-fluid methods (VOF) in [8–10], while meshfree methods have started to appear such as the particle finite element method (PFEM) by Oñate et al. [11] or Monte Carlo methods such as [2]. The numerical model to be applied in this study is the meshless method Smoothed Particle Hydrodynamics (SPH). Eulerian methods present some limitations that can be overcome using the Lagrangian formulation implemented in SPH. As mentioned above, numerous studies have been carried out using numerical schemes to model breakwaters, nevertheless a complete representation of the breakwater has not yet been fully modelled, but the Lagrangian model adopted here can make progress towards addressing these issues due to its meshless approach.

Despite the success of SPH in a wide variety of problems involving free-surface flows, this method also possesses some limitations. Possibly, one of its main drawbacks is the expensive computational cost in comparison with other mesh-based methods for CFD problems. This can be partially alleviated by means of hardware acceleration. A cheap and accessible option is general-purpose graphics processing unit (GPGPU) where a graphics processing unit (GPU) card is used to perform computations traditionally managed by big cluster machines with thousands of CPU cores. The open-source SPH code DualSPHysics (www.dual.sphysics.org) is capable of using the parallel processing power of either CPUs and/or GPUs making the study of real engineering problems possible. The work presented in [12] demonstrated that this code can obtain speedups of up to two orders of magnitude over an optimised single core CPU code. In particular, GPU computing enables new applications such as the numerical design of coastal breakwaters with SPH models.

SPH has been proven to be a suitable method for practical applications in coastal engineering [13–16]. The present work aims to represent a further step in the numerical modelling of coastal structures. Nowadays there is a heightening consciousness of the problems related to the protection of the seaside, due to the global climate change and strong focus on environmental aspects. The customers and social communities ask for reliable results to take quick decisions as soon as possible. At the same time, a fully comprehensive and more complete analysis than before is requested, making the physical modelling of coastal phenomena a very challenging task, sometimes not affordable, for researchers and engineers. Thus a proper numerical modelling of the interaction between sea waves and maritime structures is becoming essential to provide reliable results and feedbacks to the customers or social communities. Continuous efforts are requested to develop suitable numerical models or to improve existing ones. The analysis described in the following paragraphs can be seen in the above depicted general framework.

DualSPHysics is used here to model the wave run-up over coastal structures with the intention to reproduce the pattern of the real structure: the study is focused on the response of a breakwater where the seaward armour layer has been reconstructed block by block in all the details. A preliminary 2-D approach is described in [17]. The capabilities of DualSPHysics to study real-life engineering problems at a reasonable computational cost, such as the design of armour block sea breakwater, is analysed. First some key parameters in breakwater crest design are described. Then the Zeebrugge prototype, geometry, composition and field measurements and laboratory tests are addressed. Starting from these data, the wave run-up is simulated on the structure, showing the relationship between porosity of the armour layer and maximum run-up heights and comparing the numerical results with analytical solutions and experimental results for regular waves. Finally, the results obtained using the DualSPHysics code are discussed. To the best of the authors' knowledge, this is the first time that wave interaction with a 3-D armoured breakwater has been simulated with SPH.

2. Breakwater design parameters

The design of coastal structures must satisfy a number of structural, functional and performance criteria, including structural stability, environmental impact and life-cycle cost. Design conditions, that aim to achieve performance criteria, include acceptable levels of hydraulic responses in terms of wave run-up, overtopping, wave transmission, and wave reflection.

The waves approaching to the structure give rise to run-up (Ru) and run-down (Rd) defined as the maximum and minimum water-surface elevation measured vertically from the still-water level (SWL). The wave run-up level is an important factor in the design of coastal defences because it determines the design of the crest level of the structure in cases where no, or only marginal, overtopping is acceptable. Examples can include dikes, revetments and breakwaters with pedestrian traffic. The relative run-up $Ru^n = Ru/H$ depends on the wave height H and wave period T of the incident wave (Fig. 2) and its interaction with the preceding reflected wave, as well as the breakwater slope angle, the surface roughness and the permeability and porosity of the slope.