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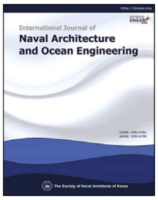

A CFD approach to rubble mound breakwater design

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ABSTRACT

The paper provides some developments of a numerical approach (“Numerical Calculation of Flow Within Armour Units”, FWAU) to the design of rubble mound breakwaters. The hydrodynamics of wave induced flow within the interstices of concrete blocks is simulated by making use of advanced, but well tested, CFD techniques to integrate RANS equations.

While computationally very heavy, FWAU is gaining ground, due to its obvious advantages over the “porous media”, i.e. the possibility of accounting for the highly non stationary effects, the reduced need of ad hoc calibration of filtration parameters and also – in perspective – the evaluation of hydrodynamic forces on single blocks. FWAU however is a complex technique, and in order to turn it into a practical design tool, a number of difficulties have to be overcome.

The paper presents recent results about this validation, as well as insight into fluid dynamical aspects.

1. Introduction

In the last ten years, advances of Computational Fluid Dynamics (CFD) have led to a decisive step in the simulation of wave actions on breakwaters, both submerged and emerged.

While physical tank models and formulas derived from them are still the main design coastal structures, 2D or even 3D flow simulation is quickly becoming standard practice; a typical procedure involves the numerical integration of Reynolds Averaged Navier—-Stokes (RANS/VOF) equations on a fixed grid, with one of the traditional turbulence models (K-eps, K-ω, RNG) and a free surface tracking procedure - this latter generally based on the now classical Volume of Fluid Method.

No exhaustive review of the literature in this field is possible, or indeed useful; however from an extensive - if now somewhat outdated - analysis of the current methods (Dentale et al., 2008), it appeared that the most commonly used code is COrnell BReaking waves And Structures (COBRAS), originally developed by Cornell University (Liu and Al-Banaa, 2004). It was subsequently applied by Losada and his coworkers e.g (Losada et al., 2008). who provided an extensive validation on many cases of engineering importance.

Tests with OTT code were carried out by Giarrusso et al. (2003). FLOW-3D® by Flow Science (Chopakatla et al., 2008; Li et al., 2004; Lopez et al., 2015) has also been widely tested. More recently FLUENT (Fang et al., 2010), PHOENICS and OpenFOAM® have been also successfully used. Finally, in a few cases specially built codes have been applied. SPH and similar particle methods are also being tested: Viccione et al. (2012) report some recent developments.

Rock mound breakwaters pose particularly difficult problems, as the flow within the interstices of blocks is strongly non stationary flow, with momentum advection, free boundary and possibly turbulence and air-water interaction, all within a very complex geometry. Current RANS/VOF practice deals with this problem by assuming that the flow within the rubble mound can be treated by the “porous media” approach, and therefore governed by the seepage flow equations (Darcy or Forchheimer, if the head loss is linear or quadratic respectively). In practice, an additional term is added to the equations to reproduce the interactions between the fluid and the inner flow paths by using homogeneous coefficients for the entire filtration domain; in some instances, an acceleration term is also introduced, leading to a Morison-like behaviour. Of course the relevant parameters have to be carefully calibrated with an ad hoc procedure on the basis of available experimental data. Such an approach was first reported in Hsu et al. (2002) later implemented in the COBRAS numerical code, i.e (Garcia et al., 2004; Losada et al., 2008).

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It is easy to see that while the “seepage” assumption is physically sound for small armour units, it certainly fails for blocks of large size, when the Reynolds number of flow inside the paths is high. Besides, the stability of a single unit cannot be evaluated with the seepage flow, so the methods are limited to the estimation of global parameters such as overtopping or global stability, and does not seem to offer any perspective of future application to the all-important problem of evaluating armour unit size and shape.

Recently, however a whole line of research (Flow Within the Armour Units - FWAU) has been devoted to model the detailed hydrodynamics within block mound structures on the basis of their real geometry. By using advanced digital techniques a fine computational grid is constructed by locating an adequate number of computational nodes within the interstices so that a complete solution of the full hydrodynamic equations can be carried out, including convective effects and, if necessary resolving the turbulence structure.

Pioneering FWAU work was carried out by using RANS-VOF (Dentale et al., 2012, 2014a, 2014b, 2014c, 2015; Cavallaro et al., 2012), while an entirely new approach, involving both CFD techniques in the interstices and numerical solid mechanics in the block themselves, is being attempted by Xiang et al. (2012), Latham et al. (2013).

2. Study methods

The first step to using FWAU is the construction of a data base of digital armour block models including natural stone blocks, simple cubes, as well as complex commercial shapes such as Accropode™, Core-loc™, Xbloc®, etc (Fig. 1).

The numerical model of the breakwater is then constructed by using a CAD 3D software system for modeling geometries: first the inner, impermeable section (including the core and the crown wall) is drawn in a conventional way; then on the sea-facing slope the armour layer is modeled by digitally overlapping the individual blocks, under the constrains of gravity, collision and friction, Fig. 2 shows some examples.

Once the geometry is fully defined, it can be imported into the CFD code to compute the hydrodynamic interactions. The results shown in the following refer to computations carried out with FLOW-3D® from Flow Science, Inc. Like other commercially available systems, FLOW-3D® numerically integrates RANS (Reynolds Average Navier–Stokes) equations by making use of the Volume-of-Fluid (VOF) method to track the free surface. It has been thoroughly tested for coastal hydrodynamics problems. Various turbulence models are available, and the results presented here are based on RNG model or K-ε.

Ad hoc experiments aimed at measuring velocities or pressures within the armour mound are extremely complex and will not be available for some time in the future; in the meantime satisfactory comparisons between FWAU results and reality has been carried out by making use of three measurable parameters about which a wealth of extensive results is available in the technical literature, i.e. the reflection coefficient; the run-up, and the overtopping.

In a typical FWAU problem, the computational domain is divided into two or more sub-grids, as the degree of resolution varies within the computational domain: generally a large one in front of the breakwater and a local, finer one within the flow paths among the blocks, since the more complex hydrodynamic interactions within the breakwater (mesh 2) obviously require a higher number of computational nodes. Also, in order to fully accommodate the 3D block mound model, the virtual geometrical set up is wider than the actual computational domain (Fig. 3).

The computational burden is naturally very heavy: in a typical test case, after appropriate convergence tests, the outer mesh for all the computations was chosen to be made up of 150.000 cells, 0.50 × 0.20 × 0.30 m, while the local one was 2.025.000 cells, 0.10 × 0.10 × 0.10 m. The computational time required for a simulation of 300 s in real time is approximately 12 h with a Intel(R) Core(TM) i7 CPU, 2.67 GHz Processor.

Some images of the 3D configurations of the free surface are plotted in the following figure.

It is possible to notice, both for the breakwater with the armour layer only and the one with the filter layer and the toe protection, how the numerical grid used is fine enough to properly estimate the variation of the hydrodynamic quantities inside the flow path and along the boundary of the individual armour element. This condition is most visible in the 3D reconstruction of the free surface (Fig. 4) where the effects of waves on the breakwater can be seen with more detail.

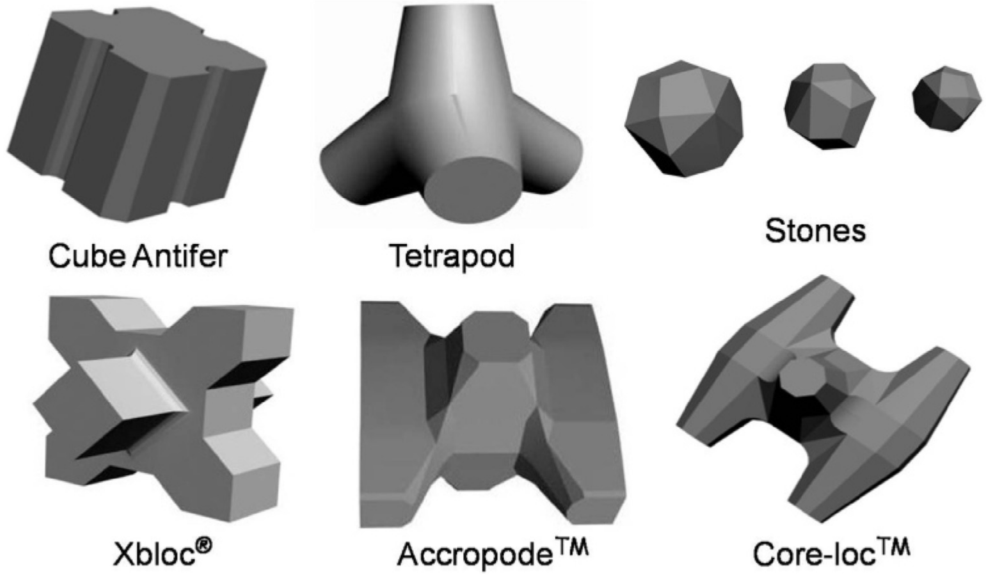

Fig. 1. Virtual 3D models of stones.

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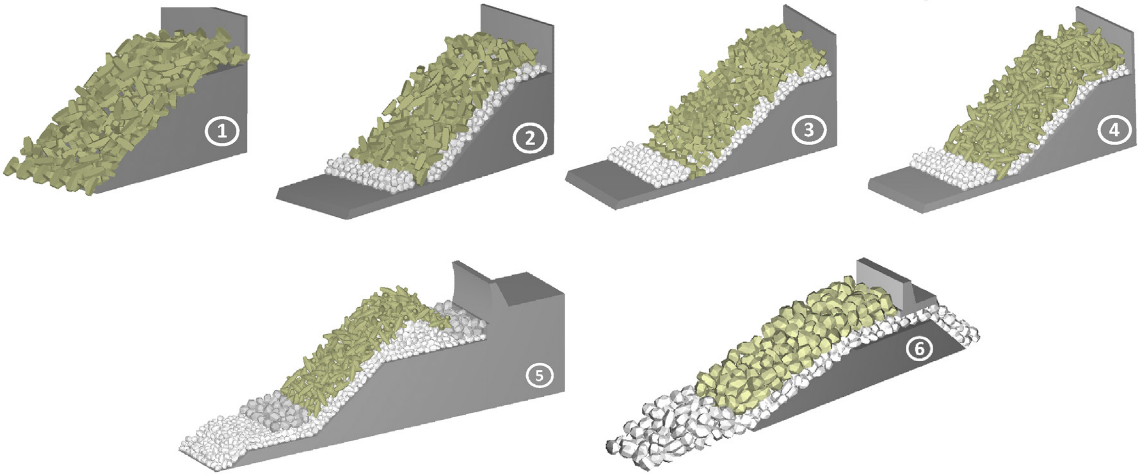

Fig. 2. Virtual models of the breakwater.

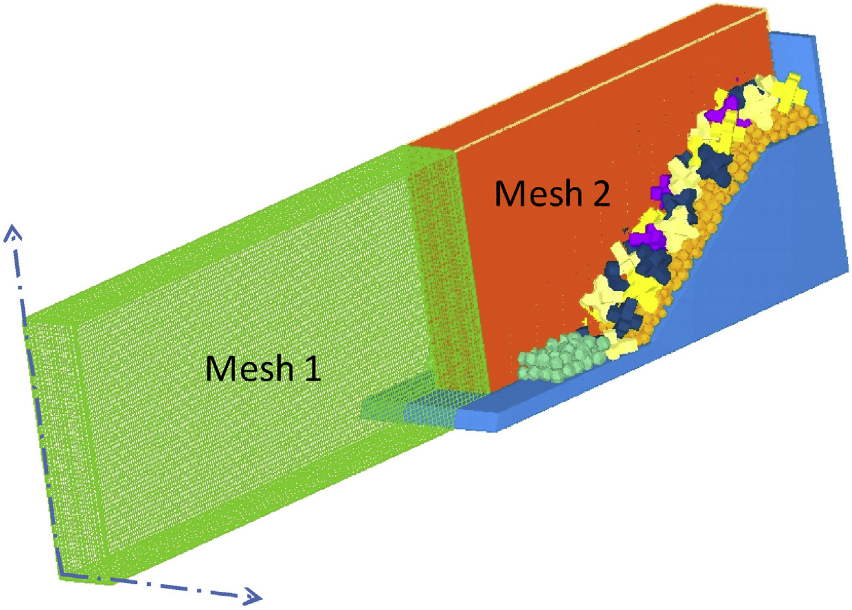

Fig. 3. Computational domain.

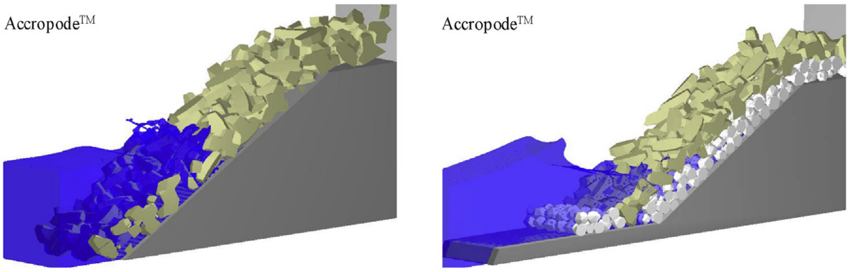

Fig. 4. 3D Results (Free surface evolution) Snapshots.

It is interesting to see, in the following figures, how the hydrodynamics computed with FWAU compares with the results of the porous media approach: a consistent turbulent kinetic energy develops among the flow paths inside the blocks, mostly due to the strong velocity gradients. This influences the wave profile evolution at the breakwater, giving a different shape from the one obtained with the "porous media" model, which produces an entirely different turbulence structure outside it.

The velocity in any given point within the rock mound is highly non stationary, as it could be expected (Fig. 5). In the location

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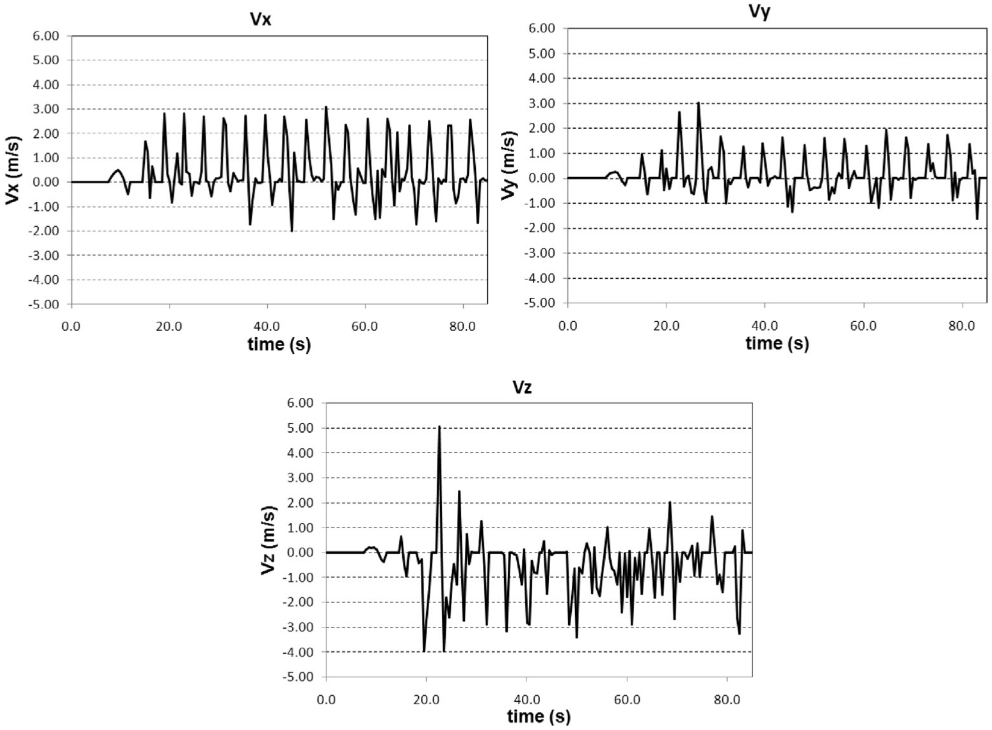

Fig. 5. Velocity graphs.

shown the velocity along the three axis (vertical Z) and horizontal X, Y present about the same order of magnitude.

Typical values for the Reynolds Number, defined as V_o*D_{50}/ν, where V_o is the average velocity and D_{50} the nominal diameter of the blocks, can be as high as 10^6 (Reynolds Number). A Strouhal number, defined as D_{50}/(T. V_o) - T being the wave period - may also be of importance and its value is highly variable. The mesh size is of course of paramount importance towards computational accuracy and convergence test are necessary to provide adequate values for the ratio between Δ_x, Δ_y (grid size) and D_{50}, a typical value of the ratio is about 0.05.

3. Results and discussion

3.1. Reflection coefficient

Wave reflection near a maritime structure has been studied for many years in order to define the parameters that most affect the phenomenon. Based on experimental tests, several equations have been defined, according to the geometrical characteristics of the structure and the waves, to quantify the reflection coefficient Kr defined as the ratio Kr = Hr/Hi between reflected (Hr) and incident (Hi) wave. A vertical impermeable structure will have a Kr of about 1, while a porous slope one will have a Kr ≪ 1.

In order to validate the FWAU procedure described above comparisons were made between the numerical Kr and the experimental work proposed by Zanuttigh and Van der Meer (2006), where a substantial number of experimental tests were carried out in a scale model or prototype. The incident wave heights are determined through the two probes method proposed by Goda and Suzuki (1976) to separate the incident from the reflected waves (Fig. 6).

All the FWAU results stay well within the experimental result; besides, as it could be expected, a higher reflection coefficient results from the numerical simulations carried out for the structure 1 shown in Fig. 2, without a filter layer (blue dots).

3.2. Run-up

The evaluation of the wave motion along the external face of the breakwater (run-up) is of the greatest importance in the design of marine works. This phenomenon heavily influences the choice of the design height, especially in order to limit overtopping events.

In the following, a comparison is made between the run up values obtained by an equation by Van der Meer and Stam (1992), and those obtained by the FWAU tests. The numerical values were evaluated by processing the time series (Fig. 7b) obtained by considering the water height over the breakwaters slope, as shown in (Fig. 7a).

As can be seen from Fig. 8, the numerical data yield a good fit with Van der Meer e Stam's results.

3.3. Overtopping

For a preliminary validation of the proposed methodology to analyze the overtopping phenomenon, one real breakwater has been investigate (in the following “Sant'Erasmo”). This is a conventional large quarry stone breakwater designed for the new port of Sant’Erasmo (Catania-Sicily) and illustrated in Fig. 9a and b, which has been the object of extensive laboratory tests and is taken in the following as a reference (Cavallaro et al., 2012).

The Sant’Erasmo experiments were carried out in the wave flume of the Hydraulic Laboratory of the University of Catania (Italy). The flume, with lateral transparent glass walls, is 18 m long, 3.60 m wide and 1.20 m deep. A flap-type wavemaker allows both regular and irregular wave series to be reproduced. Physical modeling was carried out by using a geometrically undistorted 1:80 scale with respect to the prototype and by guaranteeing Froude similarity. The stability of the structure was measured through imaging methods by considering both the relative number of

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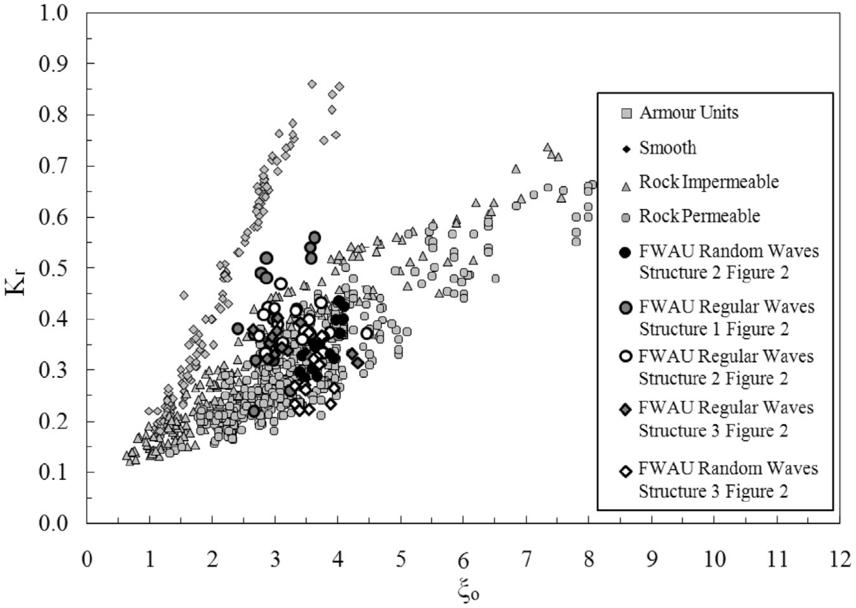

Fig. 6. Examples of Numerical K_r (reflection coefficient) vs. physical data as a function of the Irribarren parameter ξ_0 (Zanuttigh and Van der Meer, 2006).

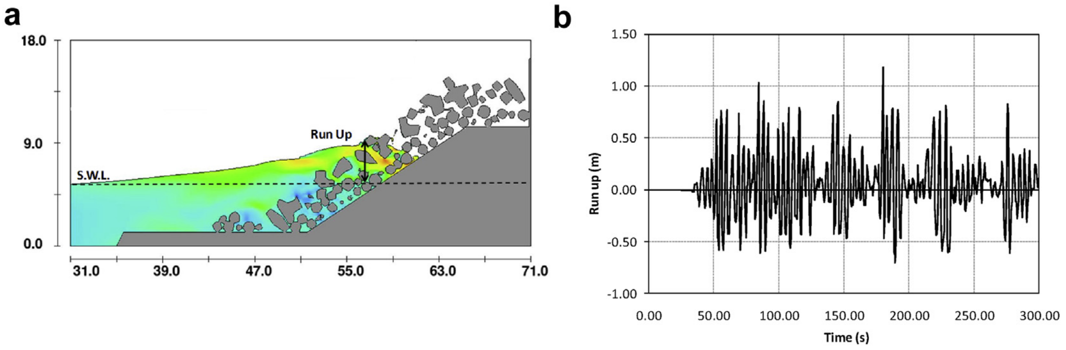

Fig. 7. a Run-up time series evolution. b Example of wave motion's frame.

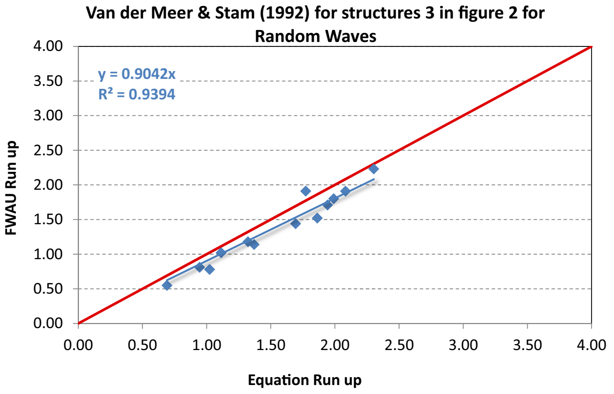

Fig. 8. Correlations between FWAU simulated run up and experimental equation.

displaced elements and the damage parameter based on the relative eroded area. In particular, to this aim a 2D measurement technique based on the use of structured light has been applied to obtain a continuous monitoring of the damage evolution (Foti et al., 2011). Three resistive gauges were located in front of the structure in order to evaluate the wave reflection coefficients by means of the Goda and Suzuki (1976) method. Finally measurements of the average wave overtopping discharge have been obtained.

The most relevant results of the tank tests (Qmeas), and of the RANS/VOF computations carried out with the full simulation of the flow among the blocks, as described in the previous paragraphs, (QNumerical3D) are reported in Fig. 10, where Q* and R* are given by:

$$Q^* = \frac{q_{ov}}{\sqrt{gH_{m0}}}\sqrt{\frac{s_0}{tan\alpha}}; \tag{1}$$

$$R^* = \frac{R_c}{H_{m0}}\sqrt{\frac{s_0}{tan\alpha}}\,\frac{1}{\gamma_b\gamma_\beta\gamma_v}; \tag{2}$$

R_c is the breakwater crest height; H_{m0} the wave significant height and s_0 its slope; q_{ov} the overtopping flow; tanα the armour slope; γ_b, γ_β and γ_v empirical parameters as in Van der Meer (CIRIA et al., 2007). The value obtained by the latter formula are also reported in the same picture (Qtheo).

Within the limits of the usual approximation of this kind of experiments, the 3D RANS/VOF methods compare well with the tank test and it allows to reduce the overestimate obtained by using

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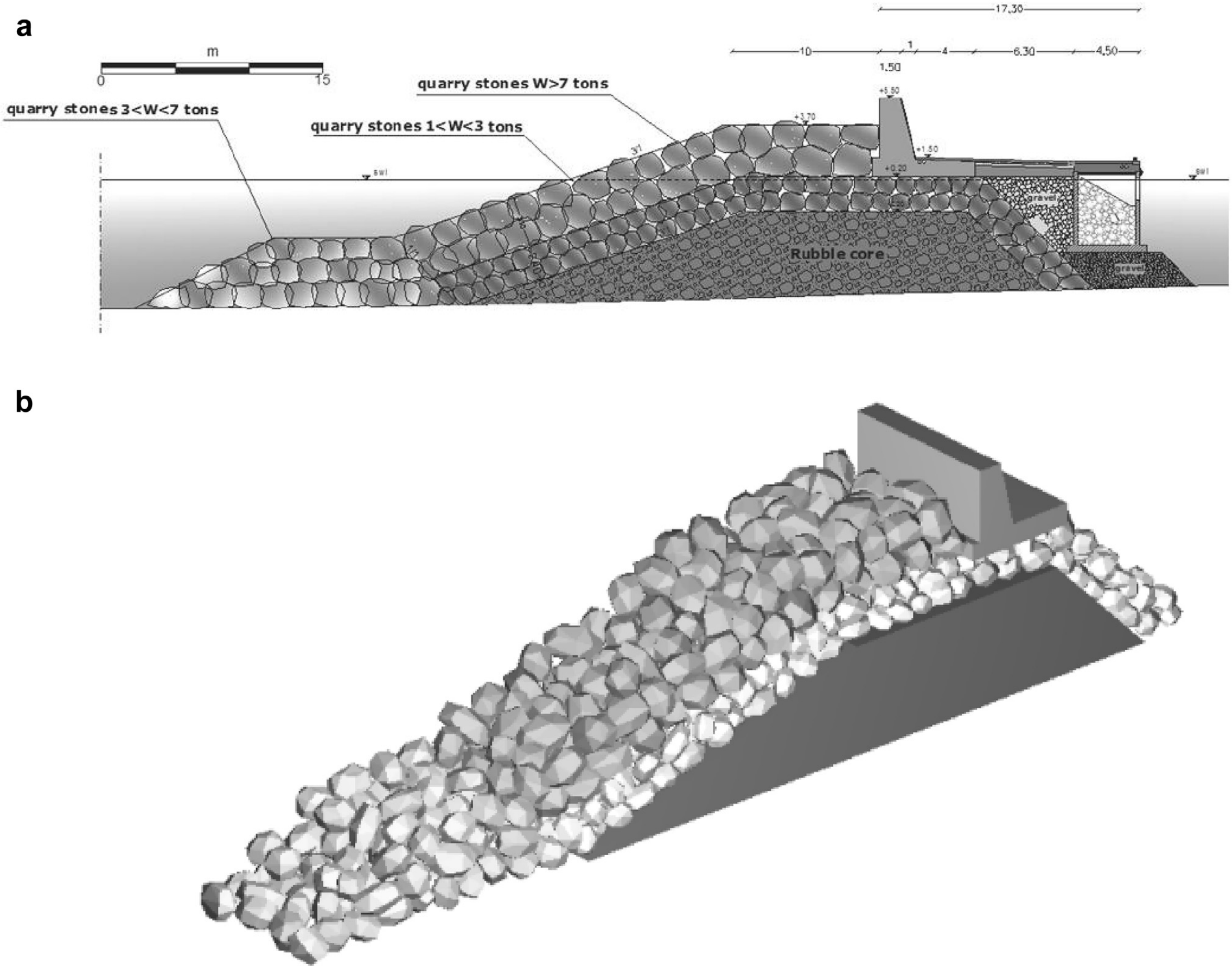

Fig. 9. a Port of Sant'Erasmo: Cross section of rubble mound breakwater. b Virtual model of Sant'Erasmo breakwater.

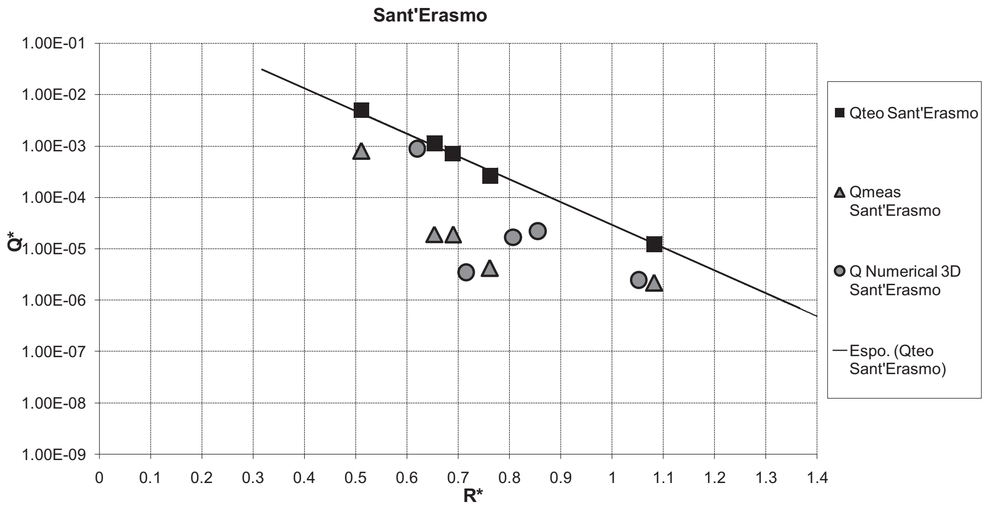

Fig. 10. Experimental and numerical results - Sant'Erasmo (Catania).

the empirical formula of Van der Meer (CIRIA et al., 2007). It is worth remembering that - unlike seepage RANS/VOF - the methods does not require any parameter calibration.

4. Conclusions

The results of a new numerical approach to model the

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hydrodynamic behavior of rock mound breakwaters have been presented.

Unlike the traditional approach where a porous media seepage flow is used to simulate the flow, the structure is modeled by overlapping individual 3D elements as it happens in the real world; a numerical grid is fitted to provide enough computational nodes within the voids so as to directly assess the flow between the blocks. The procedure implemented is based on integrating CAD and CFD techniques with a surface tracking VOF algorithm.

The results obtained for the reflection coefficient and the Run-up suggest that the described methodology could be used successfully to analyze the phenomena of interaction between the wave motion and a rubble mound with different armour layer (Brown and Dentale, 2013).

A real life overtopping problem with an unusual geometry (spilling basin) could not be properly treated with standard available formulae. Since direct experimental results were not available, an innovative RANS/VOF procedure was tested and calibrated against tank tests with a different geometry. The new, and more complex, technique produced better results than the traditional approach whereby the flow within the armour is computed with seepage flow approximation.

Results show that by using advanced digital techniques, rubble mound and block armour maritime structures can modeled on the basis of their real geometry, taking into account the hydrodynamic interactions with the wave motion: further developments might also eventually lead to evaluate the stability of the individual elements of the mound as following in Vicinanza et al. (2015), Daliri et al., 2016 and Buccino et al. (2016). The estimation of wave forces on breakwater is an important topic, because it is fundamental to design of the structures. The value of these forces, in many cases with wave breaking condition are generated actions that lead to the collapse of materials. To reduce these effects new approaches and new materials are developing (Spadea et al., 2014).

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