A new numerical approach to the study of the interaction between wave motion and roubble mound breakwaters

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Abstract: - Until recently, physical models were the only way to investigate into the details of breakwaters behavior under wave attack. From the numerical point of view, the complexity of the fluid dynamic processes involved has so far hindered the direct application of Navier-Stokes equations within the armour blocks, due to the complex geometry and the presence of strongly non stationary flows, free boundaries and turbulence. In the present work the most recent CFD technology is used to provide a new and more reliable approach to the design analysis of breakwaters, especially in connection with run-up and reflection. The solid structure is simulated within the numerical domain by overlapping individual virtual elements to form the empty spaces delimited by the blocks. Thus, by defining a fine computational grid, an adequate number of nodes is located within the interstices and a complete solution of the full hydrodynamic equations is carried out. In the work presented here the numerical simulations are carried out by integrating the three-dimensional Reynolds Average Navier-Stokes Equations coupled with the RNG turbulence model and a Volume of Fluid Method used to handle the dynamics of the free surface.
The aim is to investigate the reliability of this approach as a design tool. Therefore, for the results' validation, the numerical run-up and reflection effects on virtual breakwater (Armour in Accropode™, Core-loc™, Tetrapode or Xbloc®, toe protection and filter layer in stones) were compared with some empirical formulas and some similar laboratory tests.

Key-Words: - Numerical model, VOF, RANS equations, CFD, roubble mound breakwater, run up, reflection.

1 Introduction

The MEDUS is developing an innovative procedure that, by using CAD and CFD software, gives the possibility to study with a more detailed approach the hydrodynamic of the wave motion (overtopping, breaking, run-up, reflection, transmission) over a rubble mound structure (emerged or submerged) as well as the hydraulic stability of the armour stones. The simulations are carried out so that the filtration of the fluid within the interstices of a concrete blocks breakwater, is evaluated by integrating the Reynolds Averaged Navier-Stokes equations (RANS) inside the voids rather than making use of the widespread “porous media" approach. The structure is thus modeled, very much like in the real world or in the physical laboratory testing, by overlapping individual three-dimensional elements and then the computational grid is fitted so as to provide enough computational nodes within the flow paths.

Pioneering work with full simulation of such flow within the armour units was carried out by using RANS-VOF [10], [7], [5]; SPH (Smoothed Particle Hydrodynamics) was applied to this problem by Altomare et al. [1], while a somewhat similar approach involving CFD techniques in the interstices and numerical solid mechanics in the block themselves, is being attempted by Xiang et al. [22].

The final aim of the new computational procedure is to provide a design tool, and therefore a proper calibration should in principle involve a comparison between real and simulated fluid forces acting on the blocks within the mound.

2 The new numerical approach

The new numerical approach, must in principle be three-dimensional since the geometrical structure of the interstices among the blocks has inherently a very complex spatial structure; some successful attempts have indeed been made by the Authors to develop equivalent 2-D schemes.

Numerical reconstructions of the breakwater are thus produced by using a CAD software system for modeling 3D geometries; a data base of artificial

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blocks such as the cube, the modified cube, the Tetrapode, the Core-loc™, the Accropode™ and the Xbloc®, has preliminarily been produced, while also natural rocks can be reproduced either by using spheres of various diameters or by randomly shaped blocks (Fig 1).

Breakwaters, both submerged and emerged, are numerically reconstructed by overlapping individual blocks under the conditions of gravity, collision and friction, according to the real geometry, very much like in the case of real constructions or laboratory test model.

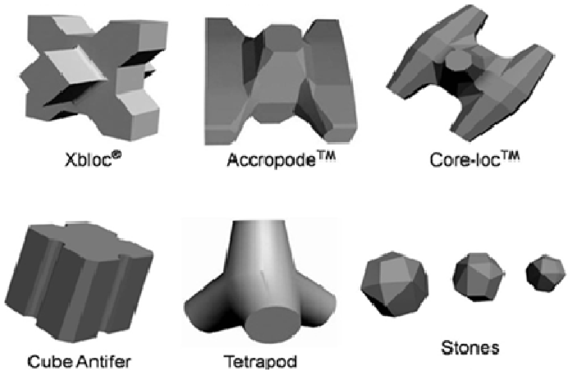

Fig. 1 Virtual 3D models of stones and armour blocks

Then, the definition of the breakwater has been improved by introducing, with the same digital technique, the filter layer and the toe protection.

Finally, to complete the structure, the armour layer has been made by different types of artificial rocks: Accropode™, Core-loc™, Tetrapode, Xbloc® (Fig. 2).

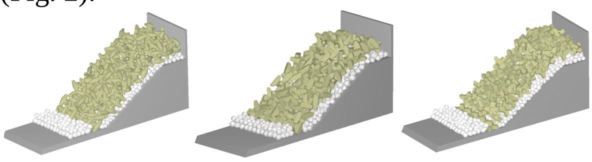

Fig. 2 Examples of virtual models of the breakwater (Core-Loc™ - left, Accropode™ - centre, Xbloc® - right)

FLOW-3D® (Flow Science Inc. 2009) was used for all calculations, like many other CFD systems employed for similar tasks, FLOW-3D® is based on the RANS (Reynolds Averaged Navier-Stokes) equations combined with the Volume of Fluid (VOF) method to apply the proper dynamic boundary conditions and to track the location of the fluid surfaces [12]. It has been thoroughly tested for coastal hydrodynamics problems, as shown in [6], [7], [8], [9], FLOW-3D®, as well as other RANS/VOF software systems, also incorporates a numerical procedure to define general geometric regions within rectangular grids, as it is essential for the construction of the breakwater block geometry.

The turbulence model associated to the RANS equations is RNG for all simulations presented in this study.

A numerical wave flume was set up in order to carry out the numerical experiments described in the following; its cross section – as shown in Figure 3 - is rather conventional, based as it is on typical experimental arrangements; its length is 170m in x direction, 4.5m in y direction and 18m in z direction. The water depth (d) in quiet conditions is 6m.

Fig. 3 Size and position of calculation meshes

The computational domain is divided into two sub-domains (Figure 4): in a typical test case, after appropriate convergence tests, the mesh 1 (general mesh) for all the computations was chosen to be made up of 243.000 cells, 0.50x0.50x0.20m, while the local one (mesh 2) was 3.240.000 cells, 0.10x0.10x0.10m.

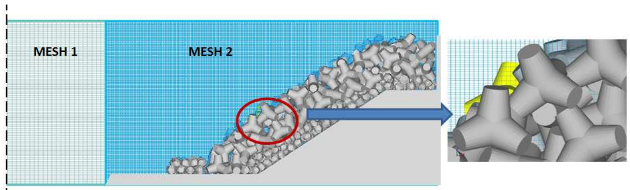

Fig. 4 General and local mesh (mesh 1 and mesh 2)

The computational burden is naturally very heavy: the computational time required for a simulation of 300 seconds in real time is approximately 12 hours with a machine type Processor Intel(R) Core(TM) i7 CPU, 2.67GHz. 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. Once the geometry of the structure, imported into the CFD, has been rebuilt and the size and the scope of the computing grids have been set, attacks wave were chosen.

2.1 Wave attacks

The simulated wave's attacks are of random type, the virtual wave generator generates wave's attacks according to Jonswap spectrum requires two input parameters: wind speed and fetch. It is important to consider, as already said above, that in numerical simulations - very much like in laboratory tests – a great deal of care should be take in order to correctly evaluate the incident wave height (in the following: Hi) by separating it from the reflected wave (in the following: Hr); in order to do so the water height time series were analyzed by using the two probes method as proposed by Goda and Suzuki [11].

Table 1. Wave characteristics at wave generator

ID SIMULATION	Fe (km)	U (m/s)
NS1	5	30
NS2	5	40
NS3	5	50
NS4	20	15
NS5	20	20
NS6	20	25
NS7	20	30
NS8	20	40
NS9	100	6
NS10	100	9
NS11	100	12.5
NS12	100	16
NS13	100	20
NS14	250	5
NS15	250	8
NS16	250	12
NS17	250	16
NS18	500	3
NS19	500	5
NS20	500	7

Errore. L'origine riferimento non è stata trovata. shows the values of fetch and wind speed that were used for the tests.

For any test the separation between incident and reflected wave is obtained using the method of Goda and Suzuki (1976) applied to all simulations.

In the sections indicated in the Figure 5 (P1 and P2) is measured the η parameter (instantaneous water's height). This parameter is used for the application of the Goda and Suzuki method [11] for the separation of the incident wave from reflected.

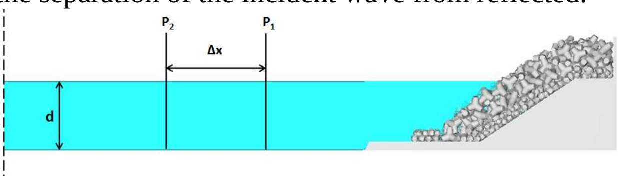

Fig. 5 Numerical Set up and Probes Pi in the numerical flume

The position of the probe 2 (P_2 in the Figure 5) is determined as L/4 and the distance between two gouges is determined in according with Goda and Suzuki prescription:

$$0.05L \leq \Delta x \leq 0.45L \qquad (1)$$

The values of L (wave's length) are determined by the dispersion equation:

$$L = \frac{gT_s^{\,2}}{2\pi}\, tgh\left(\frac{2\pi d}{L}\right) \qquad (2)$$

where T_s is the period of wave.

3 Tests and validation

In the Figures 6 and 7 the results of turbulent energy are shown, in particular in Figure 6 is shown calculation grid for the new model, while Figure 7 shows a comparison between what happens in the porous media model and what occurs in the new numerical model in turbulent energy terms.

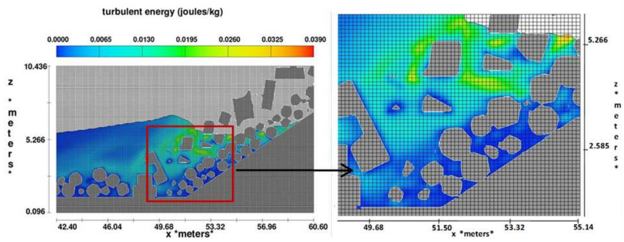

Fig. 6 Snapshot of turbulent energy (joules/kg) in local mesh

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 obviously not only cannot reconstruct the dynamic effects inside the permeable layer, but also produces an entirely different turbulence structure outside it (Figure 7) [9].

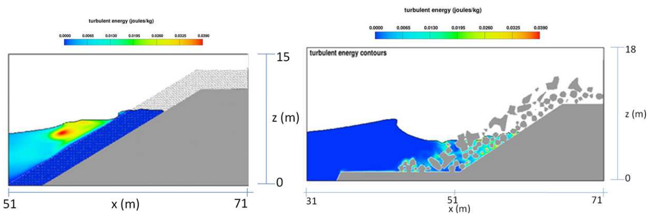

Fig. 7 Comparison between turbulent energy in the "porous media" model (left) and FWAU (right)

In order to have a preliminary validation, the results obtained through the numerical model were compared with empirical literature formulas and with physical data derived from laboratory tests. The hydraulic parameters chosen for this validation were the "run up" and the reflection coefficient "Kr".

For the comparison the parameters of a linear regression was used. For the empirical formulas, the values of wave's height was determined at the toe structure by the procedure proposed by Goda and Suzuki (1976). In all numerical analysis was made reference to the wave's height Hi, determined to toe structure by the "Goda and Suzuki" method (method of two probes), that allows to separate the incident wave conditions on the structure from those reflected.

3.1 Run up validation

In the following Figure 8 is shown a snapshot of the run up measurement for validations tests.

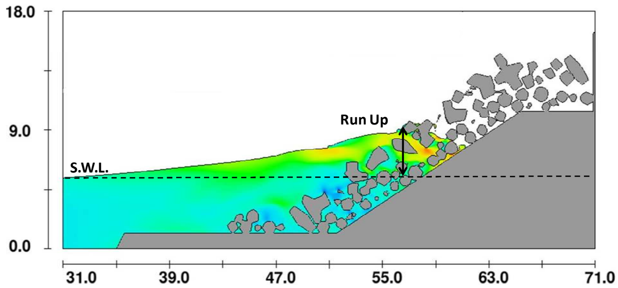

Fig. 8 Run up measurements

The values of run up were measured according to the scheme shown in Figure 8, through the snapshot of the central section of breakwater, with a frequency of 0.5 seconds, and the value of the corresponding run up was measured (Figure 9).

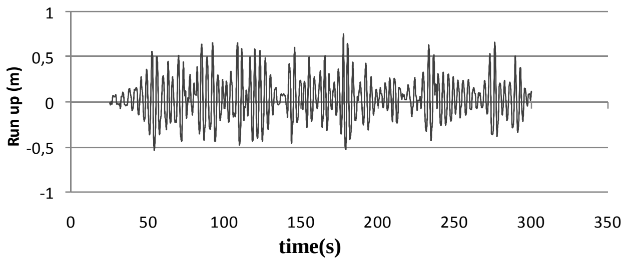

Fig. 9 Run up time series

Particularly the run up measured is the distance between SWL and the highest point of contact with the breakwater.

From the latter have been extracted the so called run-up statistics: Run up 2%: average of the highest 2% of the numerical measured Run up values; Run up 10%: average of the highest 10% of the numerical measured Run up values; Run up 1/3: average of the highest third of the numerical measured Run up values; Run up medium: average of all numerical measured Run up values.

In order to quantify the distortion, the mean error and the regression coefficient were calculated 2%, 10%, medium and significant Run up, and compared with the results by Van der Meer and Stam [20], Burcharth [3] and Van der Meer et al. [21]. The run up determined by Van der Meer & Stam formulae is the significant run up ($Ru_{1/3}$), while the run up obtained by Burcharth and Van der Meer formula is $Ru_{2\%}$.

Figure 10 and Figure 11 show some examples of the linear regression between the new numerical approach results and formulae results.

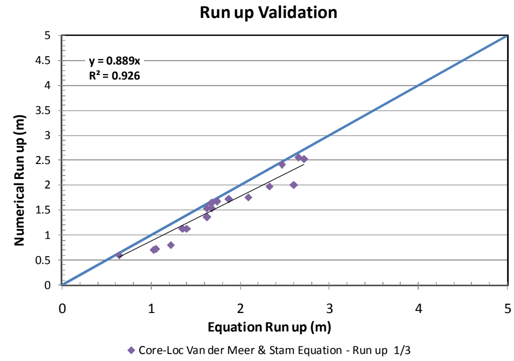

Fig. 10 Correlation between Van der Meer & Stam equation and new numerical approach for random Core-loc™

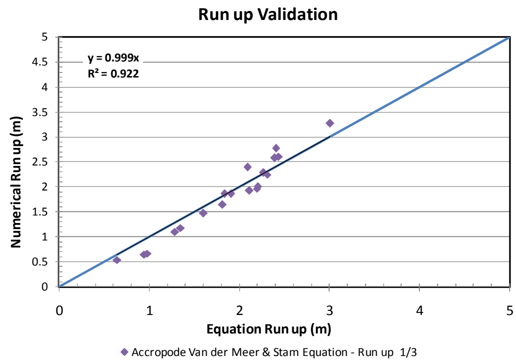

Fig. 11 Correlation between Van der Meer & Stam equation and new numerical approach for random Accropode™

In general, the trend is satisfactory, and also, at present, the model intends to provide a tool to support the physical modeling in the preliminary design phase, without replacing the latter and, therefore, the results shown are considered acceptable.

We can observe that the literature formulas tend to overestimate the run up values, as constructed, presumably, in view of design to the advantage of security. Furthermore, the purpose of the presented validation, is not to obtain identical parameters in values, but similar trends, such as to say that the presented model can be used to support the physical modeling, as a useful tool in preliminary design phase to allow a selection of design alternatives.

Consistency between numerical and experimental evidence is fully satisfactory,

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especially considering that no ad hoc calibration parameter was used for the flow in the rock mound.

3.2 Reflection coefficient validation

Wave reflection coefficient, i.e. the ratio between the reflected and incident wave Kr = Hr/ Hi, is also an useful validation parameter, as well as having some practical design application.

Computed data for Hi and Hr, derived through by the same Goda and Suzuki' s procedure discussed above, were therefore used to compare Kr against experimental tests.

In order to provide a more precise validation, with the same procedure shown above for the run up, comparisons between Numerical Kr and formulas from literature (Seelig and Ahrens,[18]); (Buerger, [2]); (Postma, [17]); (Hughes and Fowler, [13]); (Van der Meer, [19]); (Zanuttigh and Van der Meer, [23]) were carried out.

Figure 12 provides an example of correlation based on Hughes & Fowler Formula for Core-Loc^{TM}.

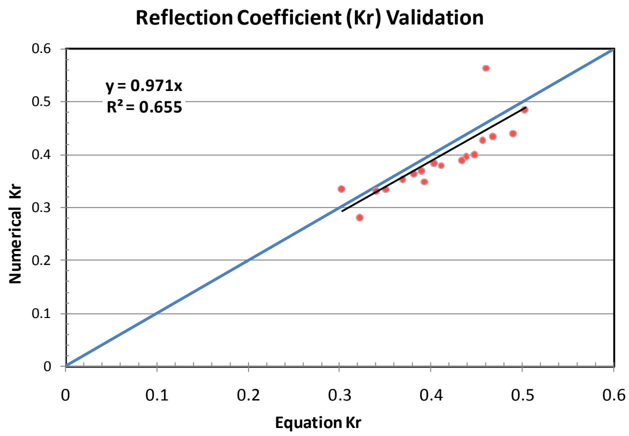

Fig. 12 Example of correlation between Literature's Formula and new numerical approach for Reflection coefficient (Kr) - Hughes and Fowler Formula (1995) for Core-LocTM.

Figure 13 provides an example of correlation based on Zanuttigh & Van der Meer Formula for Accropode^{TM}.

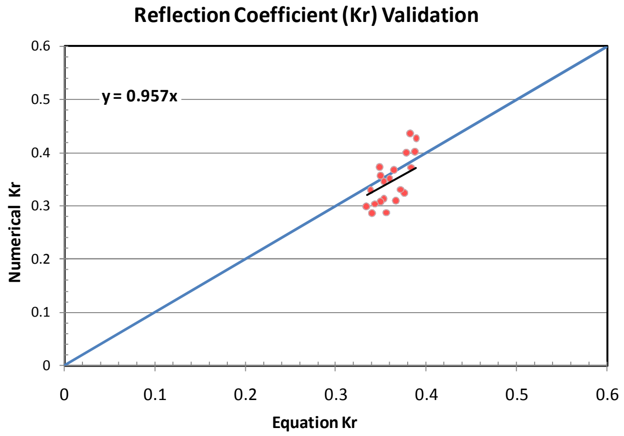

Fig. 12 Example of correlation between Literature's Formula and new numerical approach for Reflection coefficient (Kr) - Zanuttigh & Van der Meer Formula (2006) for Accropode^{TM}.

In Figure 13 and Figure 14 the numerical results for Kr are shown over the graphs proposed by Zanuttigh and Van der Meer [23], which reports a substantial number of experimental tests carried out in scale models or prototypes. In the first figure is represented the result for Core-Loc^{TM}, in the second for Accropode^{TM}.

In the following graph, on the x axis is represented the Irribarren parameter, obtained by the equation:

$$\xi = \frac{tg\beta}{\sqrt{\frac{H_i}{L}}}$$

Where:

$tg\beta = 2/3$;

H_i and L are obtained as above described.

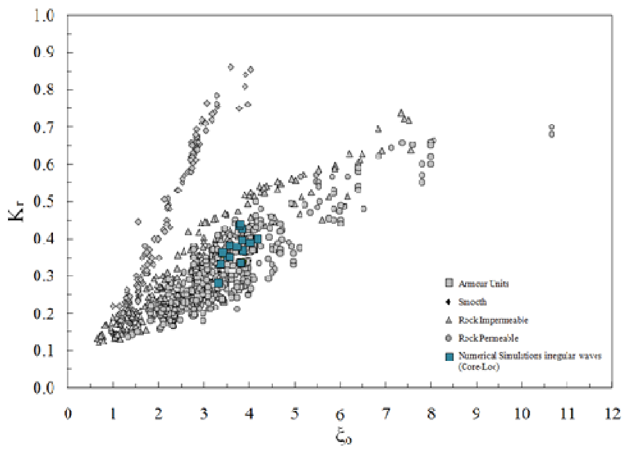

Fig. 13 Numerical Kr vs. ξ_0 - Numerical and physical data [23] for breakwater scheme (Core-Loc^{TM})

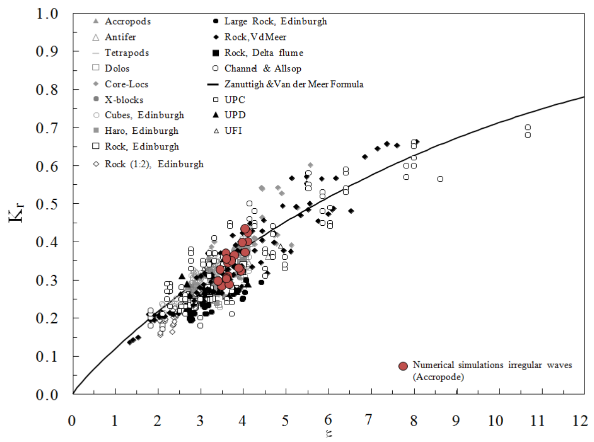

Fig. 14 Numerical Kr vs. ξ_0 - Numerical and physical data [23] for breakwater scheme (Accropode™)

The scattering of both numerical and experimental results is acceptable because all the results are however located within the same range of parameters.

Another interesting comparison can be made by using the relative water depth k_0d as an independent parameter (here $k_0=2\pi/L_0$ and d is the depth): Figures 15 and 16 show the results of Kr vs. k_0d used for constructing a new formula, based on empirical tests with regular and random waves, by Muttray et al. [15] for a given breakwater type of construction (Xbloc® single layer). On these graphs are reported the numerical results of Xbloc® and Accropode™, respectively, for a further comparison.

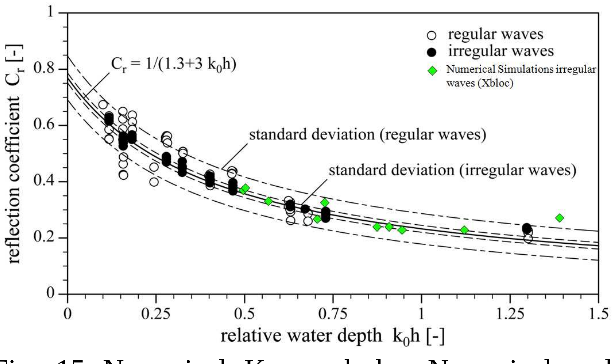

Fig. 15 Numerical Kr vs. k_0d - Numerical and physical data [15] for breakwater scheme (Xbloc®)

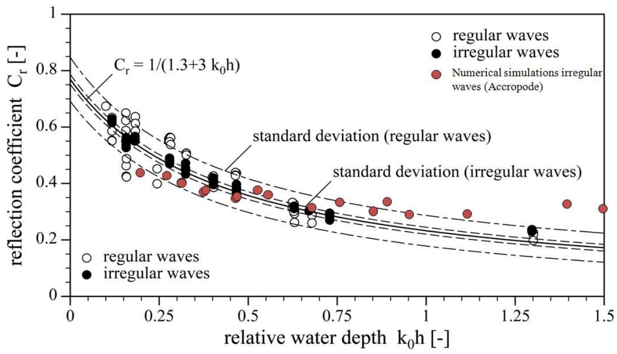

Fig. 16 Numerical Kr vs. k_0d - Numerical and physical data [15] for breakwater scheme (Accropode™)

The results appear qualitatively positive, but need further laboratory testing, as already explained above; in particular, for a relative depth greater than 0.8, the results obtained from Muttray et al. are only 3, while the results of new numerical approach, also for other types of block are about 200 and show a trend of higher reflection coefficient.

4 Forces on blocks

One of the most important perspectives of the new numerical approach is certainly the computation of hydrodynamical loads on single blocks in order to improve the safety and the cost effectiveness of coastal structure.

It is possible to evaluate, through the CFD software, the temporal evolution of the total hydrodynamic forces (pressure and shear) on a single block (Figure 16), these results do not completely solve the problem of evaluating the stability of an armor block [4], [16], which also depends on the structural connection between the blocks (pull out) [14], but they do provide some important pointers.

Accordingly, it is intended to identify some "pilot" blocks in the armour layer (Figure 17) on which to perform the calculation of the hydrodynamic forces acting (Figure 16).

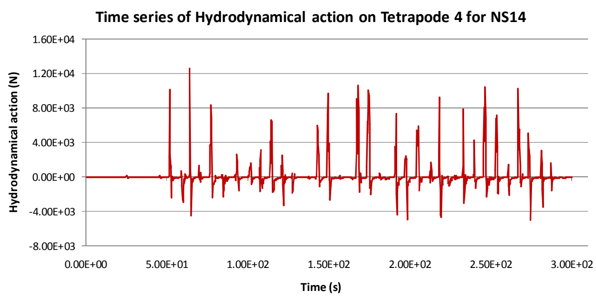

Fig. 16 Example of time series of hydrodynamical force on single block

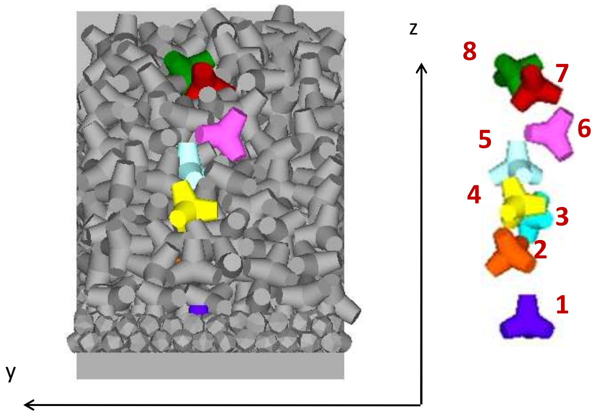

Fig. 17 "Pilot" blocks in the armour layer

In the first place the stability of the single element can be defined by comparing the force with the rock weight; it such force exceeds the block's weight, the element is potentially at risk, and as its balance within the breakwater is only guaranteed by the interlocking forces. This makes it possible to calculate a minimum block size, and also identify which of the elements would be most subjected to damage caused by extreme hydrodynamic action.

Another important result is that the highest forces are experienced by blocks nearer to the average waterline: an aspect which was already known by the construction practice but had never been quantified before and which might lead do some design improvement.

5 Conclusion

A new approach has been set up and tested to evaluate wave actions on roubble mound breakwaters within 3D - RANS - VOF hydrodynamical simulation.

Unlike the conventional procedure, whereby the flow within the rock mound is treated as a simple seepage flow, the water movement between the blocks is dealt with the full Navier Stokes equations.

A virtual structure is modeled, as it happens in real construction practice, by overlapping individual 3D elements, and a sufficiently thin numerical grid is fitted to evaluate the flow in the passages between the blocks.

An assessment of the procedure, carried out against well proven experimental result on wave reflection and run-up, has shown that the methodology described here can be successfully used without any need to calibrate physical parameters.

Tests have also been performed to evaluate the time-varying hydrodynamic forces on single blocks; while a direct experimental check of these latter result is still impossible.

By appropriately combining and tuning modern CAD and CFD techniques a relatively easy - if computationally expensive - tool has been created to investigate the interaction between a rubble mound and the wave motion thus filling as much as possible the gap between empirical formulae and physical laboratory.

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