

A numerical method to analyze the interaction between sea waves and rubble mound emerged breakwaters

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Abstract: - The paper provides some results of a new procedure, developed by MEDUS, to analyze the hydrodynamic aspects of the interactions between maritime emerged breakwaters and waves, by integrating CAD and CFD software.

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 modelled, very much like in the real world or in the physical laboratory testing, by overlapping individual three-dimensional elements (Armour in AccropodeTM, Core-locTM or Xbloc[®], toe protection and filter layer in stones), and then the computational grid is fitted so as to provide enough computational nodes within the flow paths.

This approach is meant to match closely the physical laboratory test procedure, and it is oriented at analyzing the hydrodynamic aspects of the phenomenon (overtopping, breaking, Run-up, reflection) as well as the stability of armour elements. Therefore, for the results' validation, the numerical Run-up and reflection effects on virtual breakwater were compared with some empirical formulas and some similar laboratory tests.

Key-Words: - CFD, Breakwater, Armour, Rubble Mound, Virtual Structures, Wave Run-Up, Wave Reflection, Wave Overtopping.

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 currently used approach assumes that within the rubble mound the flow can be treated by using a classical “porous media” methodology, i.e. by using, within the rubble mound, the equations that treat the filtration motion (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 using homogeneous coefficients for the entire filtration domain.

Such an approach was reported in Hsu et al. [1], later implemented in the COBRAS numerical code and finally perfected by Lara et al.[2].

The results obtained through these types of modeling, while certainly more reliable compared to the waterproof block model, present a number of drawbacks. First of all, this approach overlooks the convective aspects of the flow and the structure of turbulence; it is heavily reliant on of the numerical parameters of the filtration equations and therefore it requires a careful empirical calibration.

In the innovative procedure developed by MEDUS and proposed in this work, the simulations are carried out so that the filtration of the fluid within the interstices of the 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 [3], [4], [5], [6], [7]; SPH (Smoothed Particle Hydrodynamics) was applied to this problem by Altomare et al. [8], 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. [9].

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 and new material to build blocks [10].

2 The new numerical approach

Numerical reconstructions of the breakwater are thus produced by using a CAD software system for modeling 3D geometries; a data base of artificial blocks (Core-loc™, the Accropode™, Xbloc®), has preliminarily been produced, while also natural rocks can be reproduced either by using randomly shaped blocks (Fig.1).

Breakwaters (armour and filter layer, toe protection) are numerically reconstructed by overlapping individual blocks (Core-loc™, the Accropode™, Xbloc® and stones), one by one, 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.

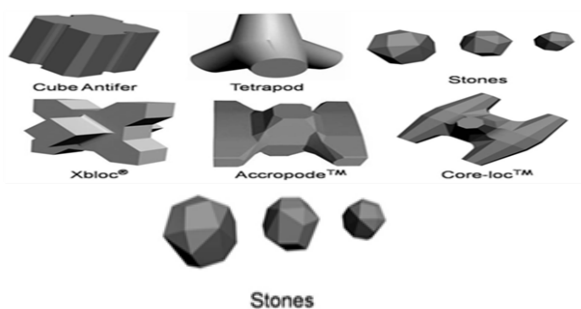


Fig.1: Virtual 3D models of stones and armour blocks

In this study are shown the results for three structures with armour layer in Core-loc™, Accropode™ and Xbloc® (Fig.2).

Defined the virtual breakwater, the geometry implemented has been imported into numerical code FLOW-3D® (Flow Science Inc. 2009) to evaluate the hydrodynamics interaction wave-structure.

FLOW-3D® is based on the RANS (Reynolds Averaged Navier-Stokes) equations combined with the Volume of Fluid (VOF) method to track the location of the fluid surfaces and various turbulence techniques such as k- ϵ , RNG or LES [11]; The turbulence model associated to the RANS equations is Re-Normalization Group (RNG) for all simulations presented in this study.

It also has some distinguishing features such as the FAVOR™ (Fractional Area Volume Obstacle Representation) method, which is used to define complex geometric regions within rectangular grids and multi-block meshing.

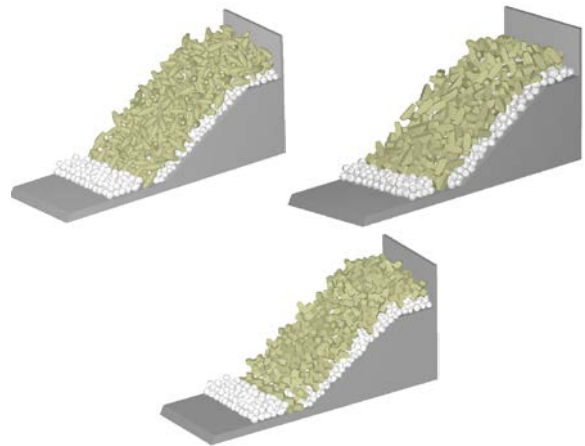


Fig.2: Examples of virtual models of the breakwater (Core-Loc™ - left, Accropode™ - right, Xbloc® - down)

It has been thoroughly tested for coastal hydrodynamics problems, as shown in [12], [4], [13], [14], [15].

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 Fig.3 - is rather conventional, based as it is on typical

experimental arrangements; its length is 250m in x direction, 4.5m in y direction and 18m in z direction. The water depth (d), below still water level, is 6m.

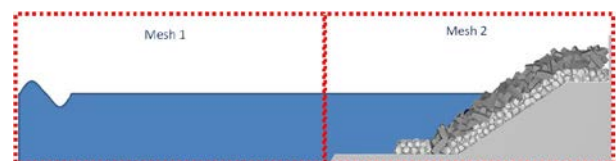


Fig.3: Size and position of calculation meshes

The computational domain is divided into two sub-domains (Fig.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.

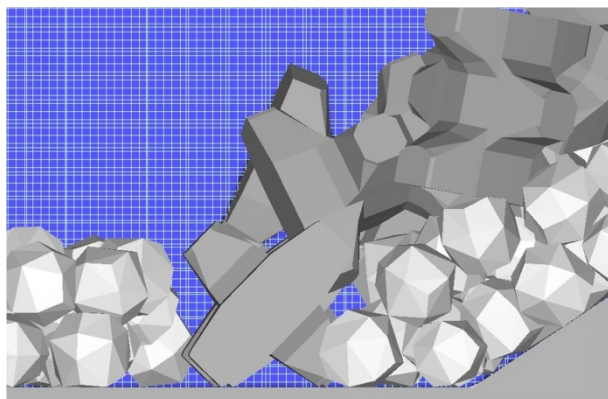


Fig.4: Example of local mesh (Armour layer in Accropode™)

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 wavemaker generate wave's attacks according to JONSWAP spectrum and 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 taken in order to correctly evaluate the incident wave height (in the

following: H_i) by separating it from the reflected wave (in the following: H_r). In this study the water height time series were analyzed by using the two probes method as proposed by Goda and Suzuki [16].

In the following Table 1 the values of fetch and wind speed that were used for the tests are shown.

Table 1: Wave characteristics at wave generator

ID SIMULATION	Fe	U
	(km)	(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	500	3
NS18	500	5
NS19	500	7

In the sections indicated in the Fig. 5 (P_1 and P_2)

is measured the η parameter (instantaneous water's height). This parameter is used for the application of the Goda and Suzuki method [16] for the separation of the incident wave from reflected.



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

The probe 1 (P_1 in the Fig.5) is positioned at a distance equal to $L/4$ from the toe structure, where L is the wave's length and is determined by the following dispersion equation:

$$L = \frac{gT_s^2}{2\pi} \operatorname{tgh}\left(\frac{2\pi d}{L}\right) \quad (1)$$

The distance between two gouges is determined according to Goda and Suzuki prescription, that respects the following condition:

$$0.05L \leq \Delta X \leq 0.45L \quad (2)$$

In the following Table 2 are shown the values of the wave height's at the toe structure determined by Goda and Suzuki method for the different structures for any simulation.

Table 2: Wave height's at toe structure for any structure

ID SIMULATION	CORELOC™	ACCROPODE™	XBLOC®
	Hi (m)	Hi (m)	Hi (m)
NS1	0.473	0.477	0.512
NS2	0.778	0.724	0.758
NS3	0.902	0.699	0.825
NS4	0.762	0.952	0.701
NS5	1.036	1.187	1.015
NS6	1.206	1.342	1.255
NS7	1.204	1.412	1.38
NS8	1.289	0.997	0.98
NS9	1.004	1.358	1.439
NS10	1.243	1.631	1.475
NS11	1.388	1.71	1.706
NS12	1.548	1.772	----
NS13	2.013	1.563	----
NS14	1.237	1.546	1.313
NS15	1.724	1.781	----
NS16	1.827	2.227	----
NS17	1.24	1.625	1.706
NS18	1.928	1.680	----
NS19	1.963	1.804	----

3 Tests and validation

In the Fig.6 and Fig.7 the results of turbulent energy in the central section of breakwater are shown, in particular in Fig.6 is shown calculation grid for the new model, while Fig.7 shows a comparison between what happens in the porous media model (left) and what occurs in the new numerical model (right) in turbulent energy terms.

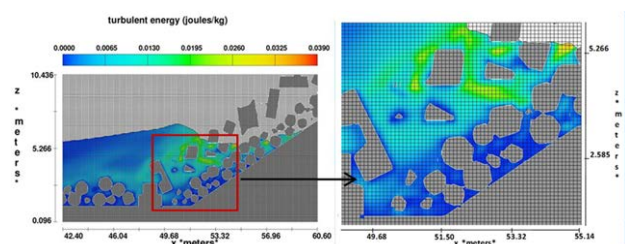


Fig.6: Snapshot of turbulent energy (joules/kg) in local mesh

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 (Fig.7).

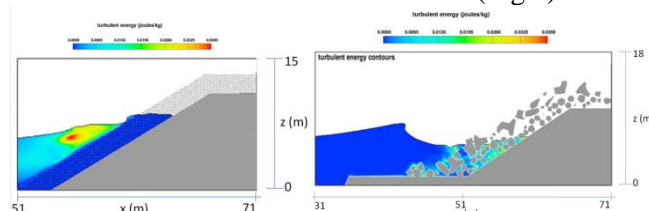


Fig.7: Comparison between turbulent energy in the “porous media” model (left) and new method (right)

In order to have a preliminary validation of the procedure, 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 “ K_r ”.

For the comparison the parameters of a linear regression was used. In the empirical formulas, for the wave's height, have been used the values in the Table 2.

3.1 Run-up validation

In the following Fig.8 is shown a snapshot of the Run-up measurement for validations tests.

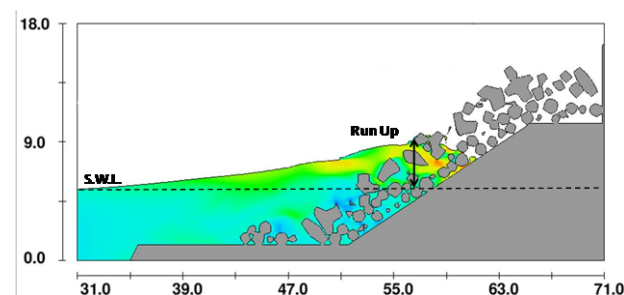


Fig.8: Run-up measurements

The values of Run-up were measured according to the scheme shown in Fig.8, through the snapshot of the central section of breakwater, with a frequency of 0.5 seconds (Fig.9).

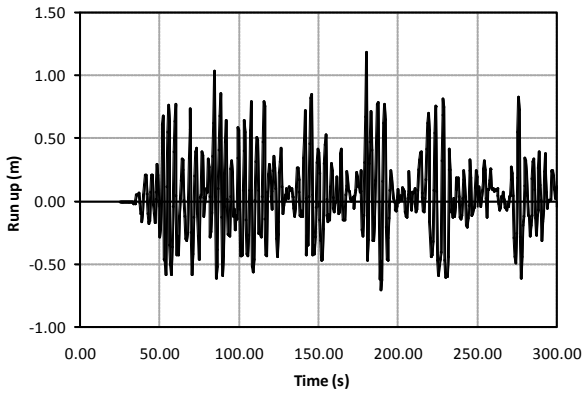


Fig.9: Run-up time series

From the latter have been extracted the so called

statistics Run-up: $R_{u_{2\%}}$, $R_{u_{10\%}}$, $R_{u_{1/3}}$, $R_{u_{medium}}$.

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 [17], Burcharth [18] and Van der Meer et al. [19]. The Run-up determined by Van der Meer & Stam formulas is the significant Run-up (1/3), while the Run-up obtained by Burcharth formula is Run-up 2%.

Figures 10, 11, 12, 13, 14 show some examples of the linear regression between the new numerical approach results and formulas results.

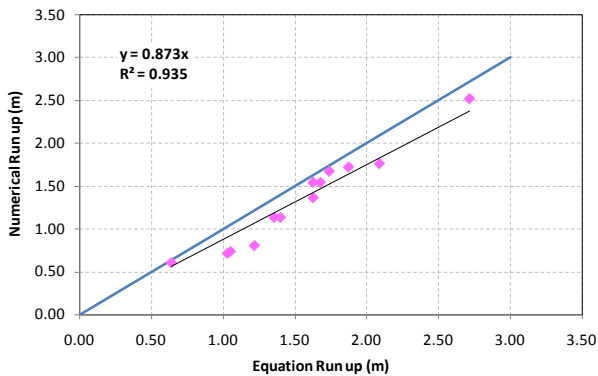


Fig.10: Correlation between Van der Meer & Stam equation and new numerical approach for structure in Core-locTM

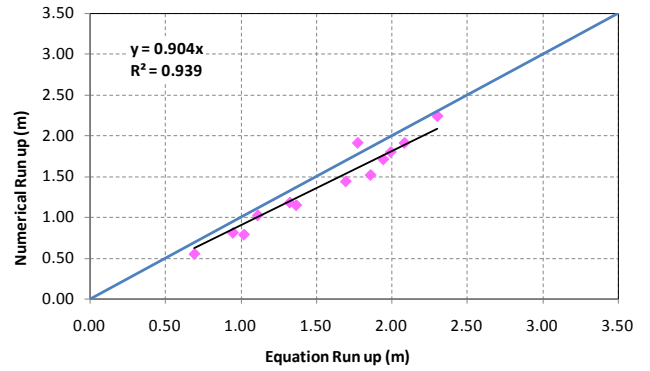


Fig.11: Correlation between Van der Meer & Stam equation and new numerical approach for structure in Xbloc[®]

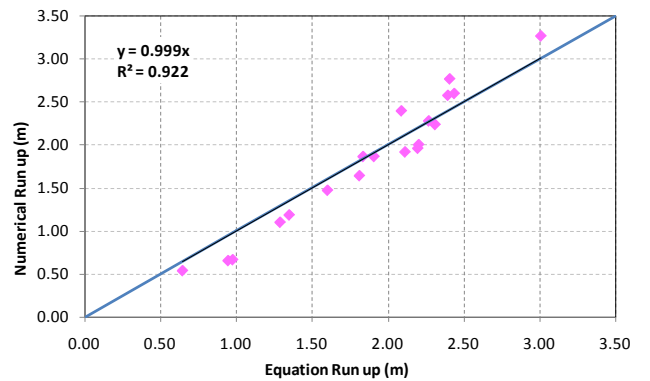


Fig.12: Correlation between Van der Meer & Stam equation and new numerical approach for structure in AccropodeTM

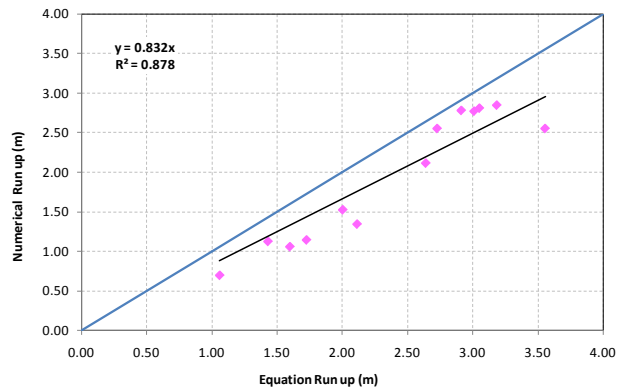


Fig.13: Correlation between Burcharth equation and new numerical approach for structure in Xbloc[®]

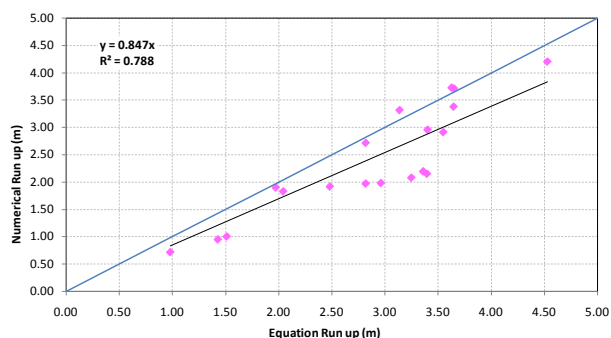


Fig.14: Correlation between Burcharth equation and new numerical approach for structure in Accropode™

In general, the trend is satisfactory, and 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.

We can see that the regression is worse for the Burcharth formula, this happens because the values considered for this regression are fewer in number.

A statistical parameter used to evaluate the fit of the correlation is the mean error which was determined through the following relationship:

$$Mean\ error = \frac{1}{n} \sum_{k=1}^n \frac{X_{fk}}{Y_{nk}} \quad (4)$$

where

= -th Run-up as calculated by the literature

formula;

= -th Run-up calculated by the numerical

simulation.

In the following Table 3 the results for mean error for each formula are shown:

Table 3: Run-up - Mean error for each formula for several structures

	MEAN ERROR		
	CORELOC™	XBLOC®	ACCROPODE™
BURCHART Ru 2%	1.42	1.29	1.26
VAN DER MEER & STAM - Ru 1/3	1.17	1.14	1.08

Consistency between numerical and experimental evidence is fully satisfactory, 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 $K_r = H_r/H_i$, is also an useful validation parameter, as well as having some practical design application.

Computed data for H_i and H_r , derived through the same Goda and Suzuki's procedure discussed

above, were therefore used to compare K_r against experimental tests.

In order to provide a more precise validation, with the same procedure shown above for the Run-

up, comparisons between Numerical K_r and formulas from literature (Seelig and Ahrens,[20]); (Buerger, [21]); (Postma, [22]); (Hughes and Fowler, [23]); (Van der Meer, [24]); (Zanuttigh and Van der Meer, [25]) were carried out.

Figures 15, 16, 17, 18 provide some examples of correlations with above cited formulas.

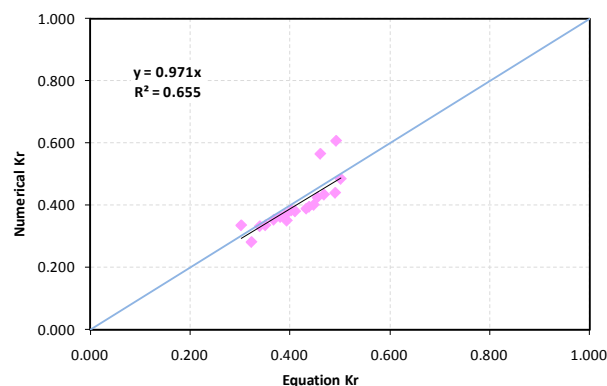


Fig.15: Example of correlation between Literature's Formula and new numerical approach for Reflection

coefficient (K_r) - Hughes and Fowler Formula (1995) for Core-LoC™

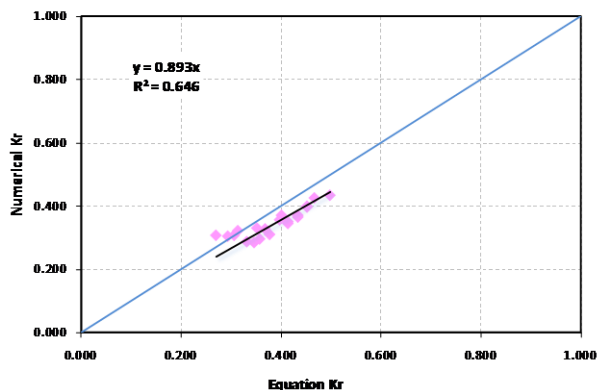


Fig.16: Example of correlation between Literature's Formula and new numerical approach for Reflection

coefficient (K_r) - Hughes and Fowler Formula (1995) for AccropodeTM

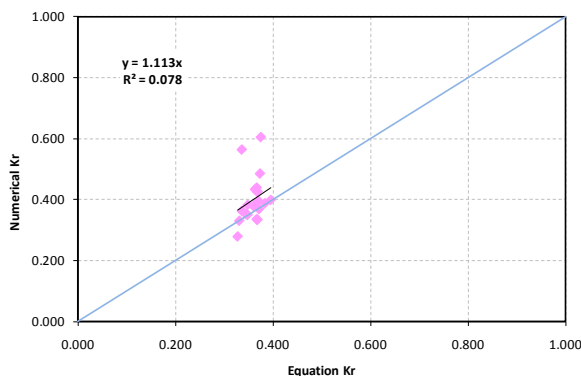


Fig.17: Example of correlation between Literature's Formula and new numerical approach for Reflection

coefficient (K_r) - Zanuttigh & Van der Meer Formula (2006) for Core-LocTM

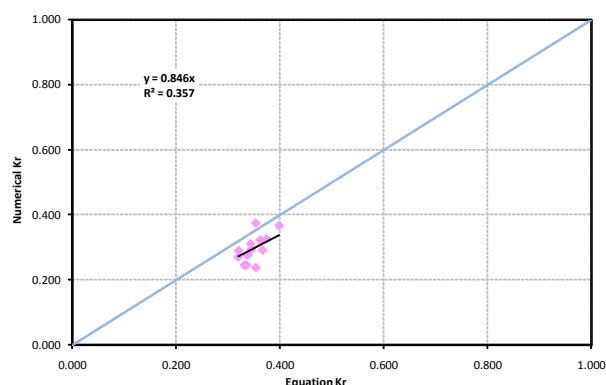


Fig.18: Example of correlation between Literature's Formula and new numerical approach for Reflection

coefficient (K_r) - Zanuttigh & Van der Meer Formula (2006) for Xbloc[®]

In the following Table 4 the results for mean error for each formula are shown.

Table 4: Reflection coefficient (K_r) - Mean error for each formula for several structures

	MEAN ERROR		
	CORELOC TM	XBLOC [®]	ACCROPODE TM
Seeling & Ahrens	1.04	1.29	1.19
Buerger et al.	0.83	0.99	0.95
Postma	0.84	0.99	0.96
Van der Meer	0.88	1.07	1
Hughes & Fowler	1.04	1.13	1.11
Zanuttigh & Van der Meer	0.93	1.13	1.06

In figures 19, 20, 21 the numerical results for the reflection coefficient for each structure are shown over the graph proposed by Zanuttigh and Van der Meer [25], which reports a substantial number of experimental tests. In this graph on the x axis is represented the Irribarren parameter ξ , on the y axis the reflection coefficient.

The Irribarren parameter is determined by the following relationship:

$$\xi = \frac{\tan\beta}{\sqrt{\frac{H_e}{L}}} \quad (3)$$

where β is the structure's slope, H_e is the wave's height at the toe structure and L is the wave's length.

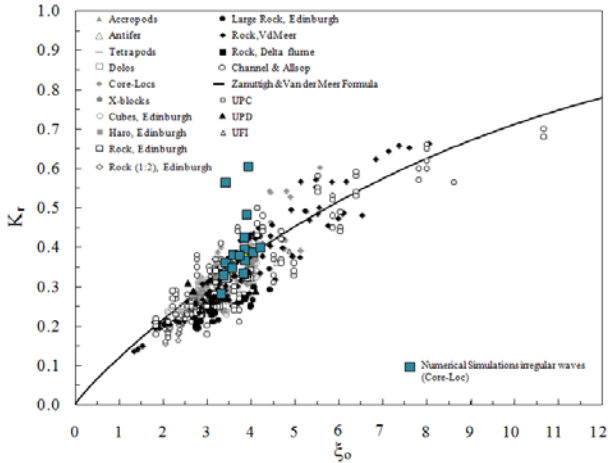


Fig.19: Numerical K_r vs. ξ_0 - Numerical and physical data [25] for breakwater with armour layer in Core-LocTM

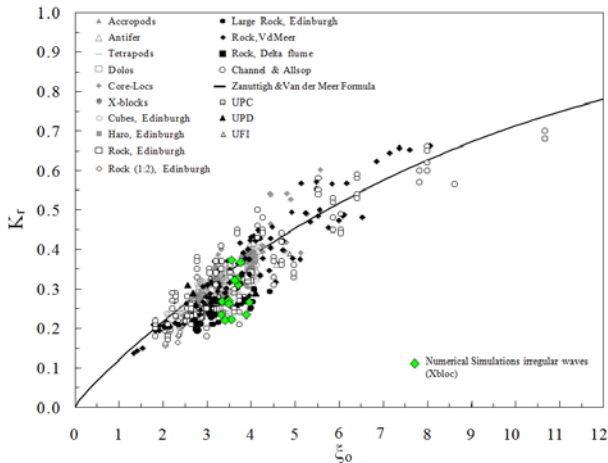


Fig.20: Numerical K_r vs. ξ_0 - Numerical and physical data [25] for breakwater with armour layer in Xbloc[®]

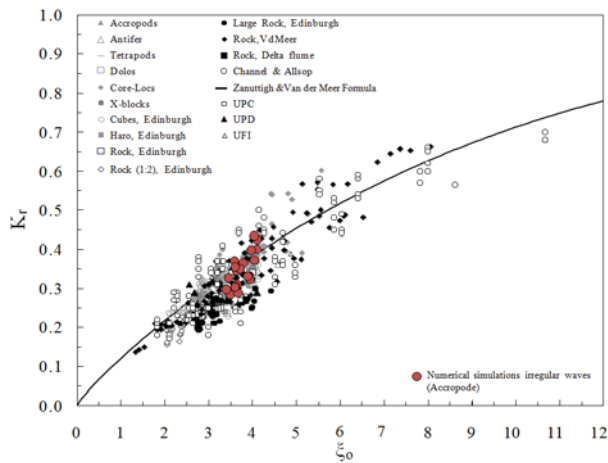


Fig.21: Numerical K_r vs. ξ_0 - Numerical and physical data [25] for breakwater with armour layer in AccropodeTM

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 $k_0 d$ as an independent parameter: Fig.22 and Fig.23 show the

results of K_r vs. $k_0 d$ for the structures with armour layer in Xbloc[®] and AccropodeTM overlapped on the graph used by Muttray et al. [26] for constructing a new formula, based on empirical tests with regular and random waves [27].

The parameter k_0 is given by the following relationship:

$$k_0 = \frac{2\pi}{L_0} \quad (4)$$

where L_0 is:

$$L_0 = \frac{gT^2}{2\pi} \quad (5)$$

The blocks used by Muttray et al. for the empirical tests are Xbloc[®], indeed the alignment of the numerical results for the structure with Xbloc[®] is very good, while the alignment to other structures (for example the structure with the armour layer in AccropodeTM - Fig.23) is less good than that shown by Xbloc[®].

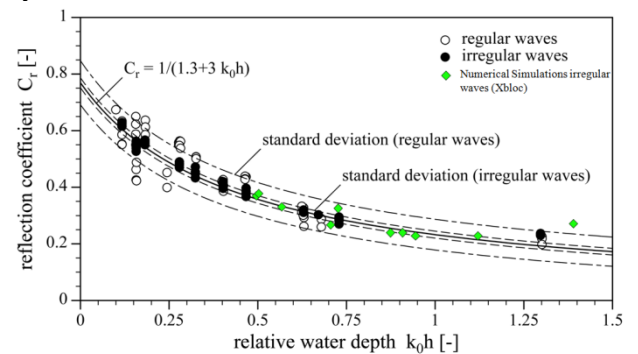


Fig.22: Numerical K_r vs. $k_0 d$ - Numerical and physical data [26] for breakwater with armour layer in Xbloc[®]

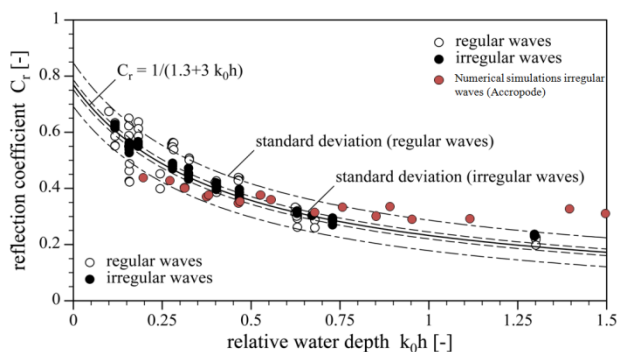


Fig.23: Numerical K_r vs. k_0d - Numerical and physical data [26] for breakwater with armour layer in AccropodeTM

The results appear qualitatively positive, but need further laboratory testing, in particular, the results obtained from Muttray et al. for a relative depth greater than 0.8 are only 3.

4 Further works: 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 [28], [29], [30].

It is possible to evaluate, through the CFD software, the temporal evolution of the total hydrodynamic forces (pressure and shear) on a single block (Fig.25, Fig.26), these results do not completely solve the problem of evaluating the stability of an armor block [31], [32], which also depends on the structural connection between the blocks (friction and interlocking), but they do provide some important pointers.

Accordingly, it is intended to identify some “probe blocks” in the armour layer on which to perform the calculation of the hydrodynamic forces acting (Fig.24). In the Fig.25 and Fig.26 are

reported the force time evolution vs. x and z axes for a probe block (located at interface water-air).

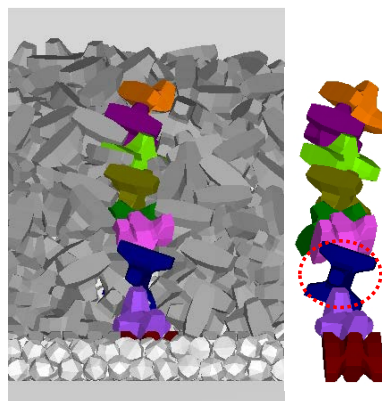


Fig.24: Probe blocks in the armour layer

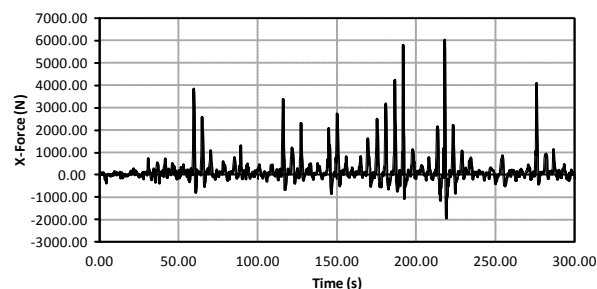


Fig.25: Example of time series of hydrodynamical X-force on single block

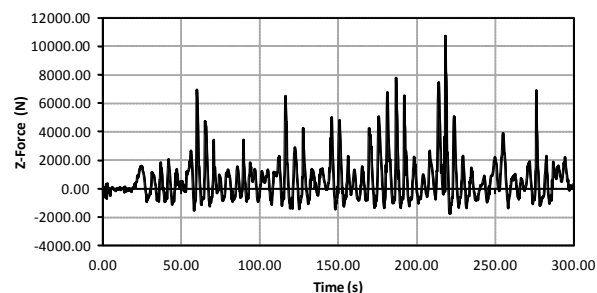


Fig.26: Example of time series of hydrodynamical Z-force on single block

In the first place the stability of the single element can be defined by comparing the force with the rock weight; if such force exceeds the block’s weight, the element is potentially at risk, and 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 Conclusions

A new approach has been set up and tested to evaluate wave actions on rubble 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 economically advantageous has been created to investigate the interaction between a rubble mound and the wave motion, this tool allows you to perform various tests on various design solutions with costs relatively insignificant.

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