International Conference on Computational Methods in Marine Engineering
MARINE 2011
L.Eça, E. Oñate, J. García, T. Kvamsdal and P. Bergan (Eds)

NUMERICAL MODELLING OF WAVES INTERACTING WITH THE BREAKWATERS OF LEIXÕES HARBOUR, PORTUGAL

MARINE 2011

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Key words: numerical modelling, wave-structure interaction, porous flow, physical modelling, video imagery techniques

Summary. Two numerical models – AMAZON, based on the non-linear shallow-water (NLSW) equations, and IH-2VOF, based on the Reynolds averaged Navier–Stokes (RANS) equations – are planned to be used to model the hydrodynamic processes around the Leixões harbour breakwaters (the existing and the submerged breakwater). In particular, the velocity field between the two breakwaters and the wave overtopping over the existing breakwater will be analyzed. This paper presents the methodology that has been used to analyze the sensitivity of the IH-2VOF results to the porous media parameters that should be calibrated. First results obtained in this study are also presented in order to illustrate this methodology.

1 INTRODUCTION

The North breakwater of Leixões Harbour, located at the North part of the West coast of Portugal, protects an oil terminal and it is subjected to overtopping and transmission of water and sediments through the porous structure. In order to mitigate the related problems, a submerged breakwater has been studied for construction in front of the existing breakwater. Defining the dimensions and characteristics of the submerged structure, as well as its position in relation to the existing structure, are some of the design difficulties. There may be also, in some cases, environmental restrictions and economic limitations.

To date, the design of the submerged breakwater has been supported mainly by empirical knowledge and, for some specific wave/water-level conditions, by physical modelling. Therefore, within the scope of the research project entitled "DESTAQ – Development of velocity measurements advanced techniques for the Interaction analysis between detached breakwater and harbour structure”[1], numerical models are also being applied to improve the knowledge about the hydrodynamic processes in the vicinity of the structures and to optimize its design. Once properly calibrated, the models can be applied and extended to situations not tested during the experimental study.

Two numerical models – AMAZON and IH-2VOF – are being used to describe the hydrodynamic processes around the Leixões harbour breakwaters, in particular the velocity field between the two breakwaters and the wave overtopping over the existing breakwater. AMAZON[2] is based on the non-linear shallow-water (NLSW) equations and it describes water motions in terms of the instantaneous total water depth and the depth-averaged velocity for regular or irregular waves. The original version of AMAZON did not explicitly account for porous flow. The development of the porous flow model was carried out recently[3] and it includes the addition of one porous layer to the original model design and the consideration of a constant porosity for the whole porous element. In this study, AMAZON will be used to evaluate the wave overtopping over the North breakwater, comparing the results with the data measured in the physical model and with the results obtained with IH-2VOF. Once the porous media characteristics are calibrated with the physical model data, AMAZON will allow a fast analysis of the structure’s behaviour for different geometries and wave conditions. IH-2VOF[4] is based on the Reynolds-averaged Navier-Stokes (RANS) equations and it describes the flow inside and outside maritime structures including permeable layers. It has already been extensively validated for low-crested structures and wave breaking on permeable slopes. The model will be used to calculate the velocity field resulting from the interaction of the submerged breakwater with the existing rubble-mound breakwater and the wave overtopping over this breakwater. Once calibrated, it will allow the evaluation of vertical and horizontal velocities in all the mesh points and their comparison with the laboratory results.

This paper presents the methodology that has been used to analyze the sensitivity of the IH-2VOF results to the calibrated porous media parameters. The analysis is mainly focused on the free surface elevation before the submerged breakwater and between the submerged and the existing breakwaters. First results obtained in this study are also presented in order to illustrate the methodology.

2 CASE STUDY

2.1. Leixões North Breakwater

The North breakwater of Leixões harbour is an unusual structure, whose geometry suffered several changes since the first layout, back in 1892. The structure was initially a submerged breakwater that due to harbour expansion was raised in the late 60’s to the crest level of +15.0 m(ZH). In the 80’s a submerged breakwater was built on the head of the North breakwater to improve its stability, defining the current configuration (Figure 1).

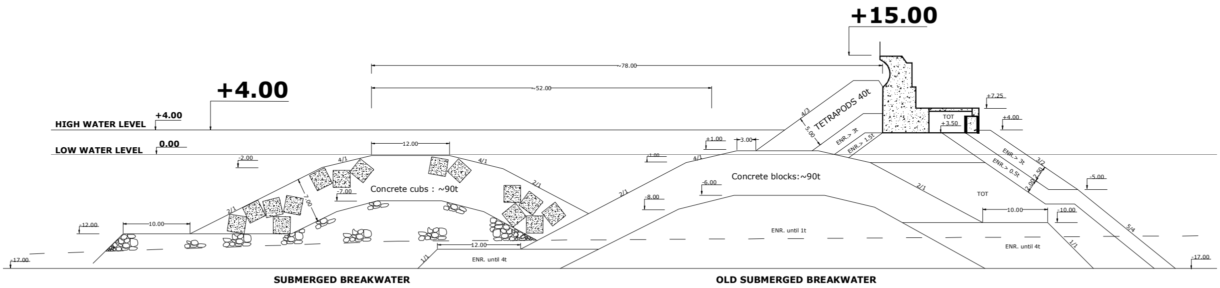

Figure 1: Cross section of the North breakwater of Leixões harbour.

2.2. Physical Model Study

The physical model tests of the North breakwater of Leixões harbour are being performed at the wave tank of the Hydraulics Laboratory of the University of Porto (Figure 2). The wave tank is 28.0 m long, 12.0 m wide and 1.2 m deep. A 0.75 m flume was built inside the wave tank to perform the 2D model tests. The model was built at a 1:60 geometrical scale and five probes were placed on the seaside of the main structure, to control the wave action and to determine the reflection of the structure and the transmission between the two structures. The test programme includes three different tide levels (0.0 m, +2.0 m and +4.0 m(ZH)), regular and irregular waves (JONSWAP spectrum) and four different wave periods (T or Tp – 13 s, 16 s, 20 s and 24 s, where T is the regular wave period and Tp is the peak of the JONSWAP spectrum). The regular wave heights (H) range from 2.0 m to 14.0 m, while the significant wave heights (Hs) range from 1.0 m to 7.0 m (all values in prototype).

Two GigE Ethernet cameras were used (UI 5220 and UI 5480 μeye – 0.8MPX with up to 90 fps; 5MPx with up to 14 fps, respectively) to analyze the flow during the tests and to record particle movements for PIV (Particle Image Velocimetry) application and velocity field characterization.

Figure 2: Model set-up.

The records were made in two different areas of the flume, in the vicinity of the submerged breakwater and in between the two breakwaters, so that all performance issues could be addressed. The high resolution camera (UI5480) was also used to capture small stretches in detail for resolution analysis comparison.

On traditional PIV and PTV (Particle Tracking Velocimetry) techniques a laser light source is used to illuminate the area of interest. In these tests a new approach is applied, using only white light (halogen focus - 2x300W). The use of white light follows the idea of defining an economic and low requirements solution that could be applied to open flume tests with wave breaking. The use of laser light source in this case was not recommended due to the presence of breaking waves and, therefore, multiphase flow.

This study is still ongoing and velocity fields are also being analyzed using Video Imagery techniques, namely PIV traditional methods. A multi-parametric probe will also be used to analyze flow characteristics.

3. NUMERICAL MODELS

3.1. AMAZON

AMAZON was originally developed at Manchester Metropolitan University[2], it is written in C++ and it comes as both a one-dimensional model, applied here, and as a two-dimensional plan model. It is based on solving the NLSW equations, which are a simplification of the Reynolds equations by depth integration. It simulates random waves and wave breaking is approximated by steep fronts represented by bores. AMAZON uses a “non-reflective wave inlet boundary condition", which is able to remove at the seaward boundary more than 98% of the energy of any waves reflected from the modelled structures. As a consequence, the seaward boundary can be set close to the structure to avoid deep water conditions, where AMAZON has limitations. It is capable of generating grid cells with any shape and varying dimensions. The output defines the free surface, depth-averaged velocities and, based on these values, discharge time-series, mean discharge and peak discharge at any location on the structure.

AMAZON has been validated for a variety of representative test problems[2] involving steady and unsteady, inviscid and viscous, and subcritical and supercritical flows. It has also been validated and extensively used to study the wave overtopping of impermeable dikes. However, AMAZON has not been systematically validated to study the overtopping of porous structures yet, since its original version did not explicitly account for porous flow. The development and initial validation of the porous flow model has been carried out only recently[3,5,6,7]. To govern the water exchange between the porous cells, both the Darcy and the Forchheimer equations are implemented.

In spite of AMAZON limitations, mainly relating to the shallow water assumptions, it is already being used for the purposes of design and flood forecasting, since wave trains of several thousand random waves are simulated rapidly.

A detailed description of AMAZON can be found in Hu[2] and in Reis et al.[5,6].

In this study, AMAZON will be applied to calculate the surface elevation and the mean wave overtopping discharge over the North breakwater of Leixões Harbour.

3.2. IH-2VOF

By taking the volume-average of RANS (VARANS) equations, Lin and Liu[8] presented a two-dimensional numerical model, nicknamed COBRAS, to describe the flow inside and outside maritime structures including permeable layers. Hsu et al.[9] extended the preliminary model by including a set of volume-averaged k-ε turbulence balance equations. The movement of the free surface is tracked by the Volume of Fluid (VOF) method. In the VARANS equations, the interfacial forces between the fluids and the solids have been modelled by the extended Forchheimer relationship, in which both linear and nonlinear drag forces are included.

IH-2VOF is a new version of the model developed at the University of Cantabria to overcome some of the initial limitations and especially to convert it into a tool for practical application. Most of these modifications have been based on the extensive validation work carried out with the model for low-crested structures and for wave breaking on permeable slopes[10,11]. The improvements cover the wave generation process and code updating; optimization and improvement of the main subroutines; improvement of input and output data definition; and the development of a graphical user interface and output data processing programs.

In this study, IH-2VOF will be used to calculate the surface elevation, the velocity field resulting from the interaction of the two breakwaters and the wave overtopping over the North breakwater.

4. MODEL CALIBRATION

To simulate the flow in a porous medium in IH-2VOF some parameters require calibration: the linear, α, and the nonlinear, β, coefficients related to the linear and nonlinear drag forces, respectively. The porosity, n, and the rock diameter, D_{50}, are usually input parameters obtained from the physical model.

In this case (see section 2.2), the structure was reproduced in the physical model by four different porous media (PM): three composed by artificial blocks (PM1, PM2, PM3) and one by small rocks (PM4). The artificial blocks are: cubes, in two different sections (PM1 and PM2), with different weights and slightly different geometries, and tetrapods (PM3), as can be seen in Figure 3. The main characteristics of the media are presented in Table 1.

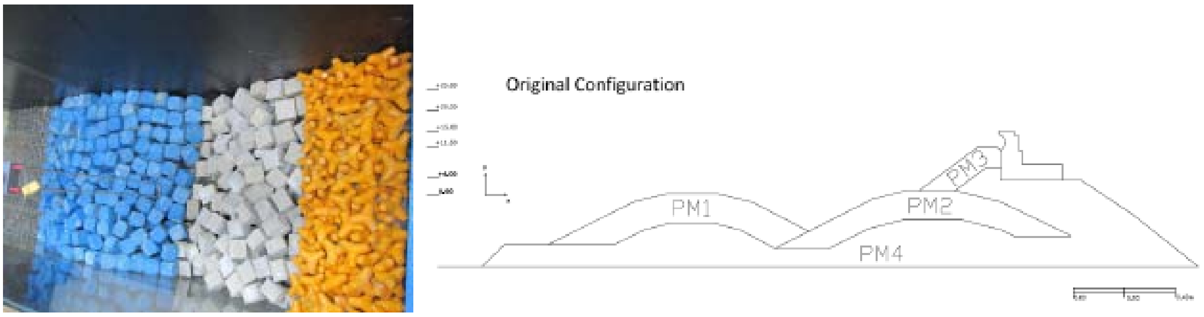

Figure 3: Experimental structure: a) top view of the physical model with the different artificial blocks used in the tests; b) schematic representation of the structure, with different porous media.

	n (%)	D_{50} (mm)	ρ (kN/m^3)
PM1 - Cubes	35 - 45	56	24
PM2 - Cubes	35 - 45	56	24
PM3 - Tetrapods	45 - 55	43	24
PM4 - Rock	20 - 35	19 - 25	18

Table 1: Main characteristics of the materials in the porous layers.

For the porous medium composed by small rock, the porosity and the diameter are easily determined in the physical model and are almost constant throughout the tests. For those specific characteristics of the porous medium there are some suggested values for α and β in the literature[10]. The recommended values for α range from 200 to 1000 and for β between 0.8 and 1.1.

For artificial blocks, the porosity depends on the block arrangement and, if the blocks move or rock during the tests, the porosity may change. Consequently, it should be calibrated as well. The diameter is calculated as the nominal diameter, based on the weight of the blocks. However, the same nominal diameter with a different shape of the block can lead to a very different porous flow. Moreover, there is no indication in the literature on the best values of α and β to be used in the case of layers composed by artificial blocks.

All these constraints, as well as the fact that the effects of one porous medium are difficult to isolate from the others, made calibration especially difficult for this case study. Additionally, the calibration should give an indication on the relative importance of each porous medium parameter in wave overtopping. This information is very important to decide on the parameters of the single porous medium that will be used in AMAZON to compute the overtopping, since the different porous media will be simulated by just one single homogenous medium in this model. Consequently, especial care has been taken in order to define which porous medium influences the most the global flow when overtopping occurs.

The methodology that has been used to analyze the sensitivity of the IH-2VOF results to each porous medium started with the definition of several base values for the porous parameters. After that, for selected cases, the sensitivity runs consisted on changing, for each porous medium at a time, the value of each parameter one by one, maintaining the other values with a constant base value, to make it easier to analyze the influence of each parameter and of each porous medium on the results. The selected cases were those where the influence of one porous medium was expected to be larger than the others, making it possible to analyze the influence of each porous medium separately. Different cases were primarily selected: firstly, two cases were chosen where no overtopping occurs and the wave reflection on PM3 (for the highest water level) and PM2 (for the lowest water level) is expected to be the main phenomenon, making PM3 and PM2, respectively, the expected key influence; secondly, a case was analyzed where breaking occurs at the submerged structure, with no overtopping, making PM1 the expected key influence.

In order to illustrate the above methodology, the first simulation case carried out with IH-2VOF is presented here.

For the simulation, the location, dimensions and geometry of the experimental structure (see section 2.2) were reproduced in the computational domain, which was 8 m long and 0.8 m high. It reproduced the main dimensions of the experimental flume, with the paddle located slightly closer to the structure than the paddle in the flume.

In order to reduce the computational time whilst assuring the required accuracy, the first set of calibration tests was run with a relatively coarse mesh. The grid was uniform both in the x and in the y directions, with a cell width, dx, of 0.01 m and a cell height, dy, of 0.005 m in the whole domain. The total number of cells was 161x851. Figure 4 shows an aspect of the computational grid close to the structure with the four porous media geometry and the (impermeable) crown wall.

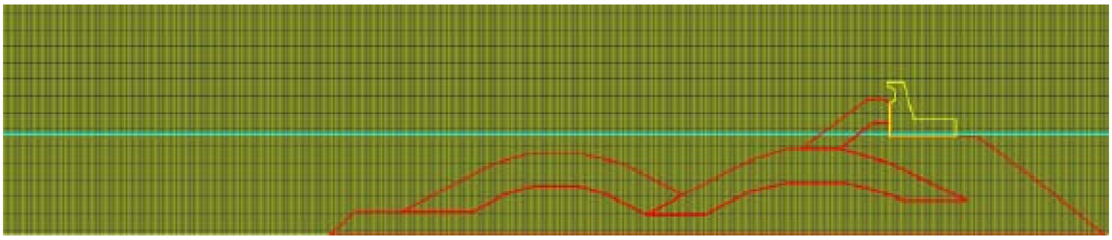

Figure 4: Aspect of the computational grid close to the structure with the four porous media geometry (in red), the impermeable crown wall (in yellow) and the sea water level.

Eight sections were considered in the numerical flume: five were located at the same positions as the wave gauges in the physical model (four between the paddle and the submerge breakwater - G3, G5, G11 and G12 - and another between breakwaters – G4); one was placed close to the paddle, in order to control the wave generation; and another two were positioned on top of the structure to compute the overtopping discharge. Each calibration test has run for 100 s in the IH-2VOF.

Several values of the porous parameters were tested in the sensitivity study. First of all, some values of the parameters α, β and n were defined as base values (Table 2). For the artificial blocks, the nominal diameter was calculated based on the weight of the blocks and for the rock medium, the mean value was adopted based on the measured range of values. For the porosity, a mean value of the measured range was adopted. The values of α and β were defined based on values used in previous simulations reported in the literature.

	n (-)	α (-)	β (-)	D_{50} (mm)
PM1	0.25	200	1.1	22
PM2	0.40	200	0.8	56
PM3	0.40	200	0.8	56
PM4	0.30	200	1.0	43

Table 2 : Values of porous media parameters adopted as base values.

After that, the value of each parameter in each porous medium was changed, one at a time, maintaining the other values constant, equal to the values presented in Table 2. The aim of this methodology is to analyze the influence of each parameter and of each porous medium on the results. Table 3 shows the values used in the calibration tests for each parameter in each porous medium. Even though some of the values are in the limit of the recommended values, it was decided to use a wide range of values in order to analyze their influence on the results.

	n (-)	α (-)	β (-)
PM1	0.25, 0.35, 0.45, 0.55	100, 200, 1000	0.5, 0.8, 1.1
PM2	0.25, 0.35, 0.45, 0.55	100, 200, 1000	0.5, 0.8, 1.1
PM3	0.4, 0.50, 0.60	100, 200, 1000	0.5, 0.8, 1.1

Table 3 Values of porous media parameters used in calibration tests.

Having all the referred constraints in mind, the sensitivity analysis started for tests with the highest water level (+4.0 m(ZH)), since for the lowest one (ZH), no overtopping was measured during the physical model tests. The first simulated condition is characterised by an incident wave height H=3.5 cm and a wave period T=1.68 s, with a water depth at the paddle h=0.35 m.

The free surface elevations computed by IH-2VOF for the different values of each porous parameter were compared with each other in order to analyze the influence of the parameters on the wave shape. The free surface elevations were also compared with those measured in the physical model tests at gauges G3, G4, G5, G11 and G12 in order to establish the optimum values of the calibration parameters. Since the wave signals of gauges G3, G5, G11 and G12 are almost sinusoidal, with almost no energy in the higher harmonics, the signals are well represented by the wave height, H, and the wave period, T. This sinusoidal wave shape is clearly seen in Figure 5, which shows the time series of surface elevation, η, measured by gauges G3, G5, G11 and G12 at the physical model between t=60 s and t=70 s. In gauge G4, located between the submerged and the existing breakwaters, the transference of energy to higher harmonics is very clear. In this case, the significant wave height, Hs, and the peak period, Tp, are analyzed together with the energy in each of the first five harmonics.

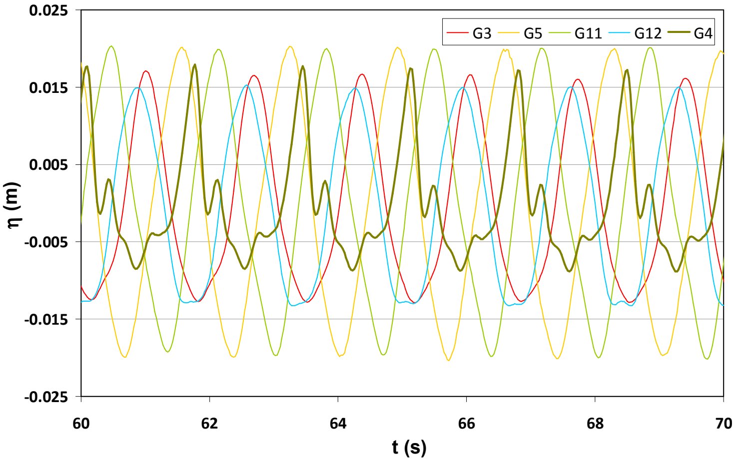

Figure 5: Time series of surface elevation measured by gauges G3, G4, G5, G11 and G12 at the physical model for H=3.5 cm, T=1.68 s and h=0.35 m.

Figure 6 shows the ratio of the values of H (or Hs) calculated with IH-2VOF ($H_{IH\text{-}2VOF}$) and H (or Hs) measured in the physical model (H_{PM}) and the ratio of the energy calculated with IH-2VOF ($S_{IH\text{-}2VOF}$) and measured in the physical model (S_{PM}) for each harmonic, for all gauges (G3, G4, G5, G11 and G12) and for the different parameters. In order to illustrate the results, the graphics with the influence of the parameters α, β, and n on H and on S are presented for PM1, PM2 and PM3, respectively. The wave period was well reproduced in the model in each one of the gauges located before the submerged breakwater, as well as the peak period at gauge G4.

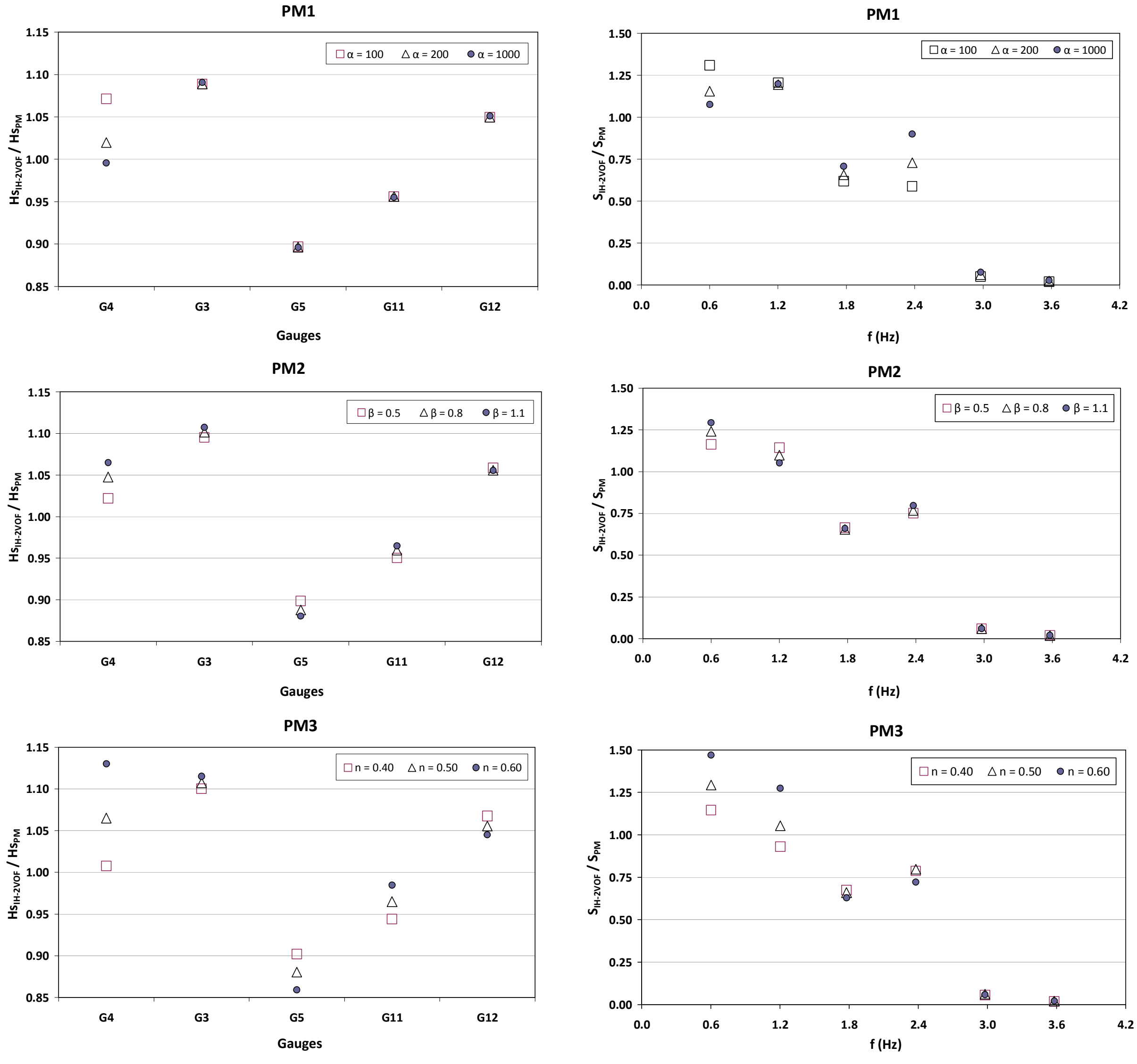

Figure 6: Influence of the porous parameters on the values of H (left) and of S (rigth) obtained in each gauge: a) α for PM1, b) β for PM2 and c) n for PM3.

The variation of α has very little influence on $H_{IH\text{-}2VOF}$ in the three porous media for all gauges. Only for PM1 and in the gauge located between the submerged and the emerged breakwaters (G4), some influence is observed, with larger values giving results closer to the experimental data (see Figure 6 a). This outcome is in accordance with Garcia et al.[10], that suggested α=1000 for submerged breakwaters.

The variation of β also shows little influence on $H_{IH\text{-}2VOF}$ for the gauges located before the submerged structure. However, the influence is visible in gauge G4 for PM1, PM2 and PM3. For PM1 and PM3 the higher values of β show a better agreement with the experimental results, whereas for PM2 is the lower value that provides the best agreement (see Figure 6 b).

The variation of n seems to be the most important influence in all porous media. This influence does not only affect gauge G4 but also the other gauges. For PM1 the effect of n is lower than for PM2 and PM3, but it affects more the gauges located before it. In other words, n is mainly changing the wave reflection on PM1. For PM2 and PM3 (see Figure 6 c), n affects all gauges, but more impact of n is found for the gauges located closer to these two porous media (G4, G12 and G11).

Summarizing, for the case analyzed here, the porosity is the parameter that influences the most the results and should be deeply analyzed in the cases where wave reflection plays an important role. The variation of the α values is important mostly for PM1 and changes in β values are relevant for all porous media, but mostly for the gauge located between the submerged and the emerged breakwaters.

Analyzing the results for gauge G4 in what concerns the transference of energy between harmonics, in general, the influence of each parameter is more important for the 1st and 2nd harmonics (see Figure 6), and the trend is consistent with that obtained for H, with the better agreement, in general, obtained for the same value of the parameters.

Having in mind that only one sensitivity case has been completed so far, that the processes of wave generation used in the laboratory and in the model are not exactly the same (even though care was taken to get the same profile in the beginning of the test, with a similar increase of the H value for both models) and that the grid used is coarse, the agreement in the wave height for this first case is reasonable. This can be confirmed in Figure 7, where the maximum differences between numerical and physical results obtained in all gauges are less than 8%. The case presented is for: α=200 for PM2 and PM3 and α=1000 for PM1; β=0.5 for PM1 and PM2 and β=1.5 for PM3; and n=0.55 for PM1 and PM2 and n=0.60 for PM3.

As referred before, in this case, the PM1 has a small influence on the results since it is submerged by a good water column. In order to analyze the sensitivity of this porous medium, a case with a small water depth will be tested. In this case, breaking is expected to occur at PM1 and the runs will take longer than for the presented case, in which the numerical tests were run on a computer with Intel Core2Quad Q6600 CPU at 2.4GHz with 2 GB of RAM and the average execution time was about 4h for 100 s simulations.

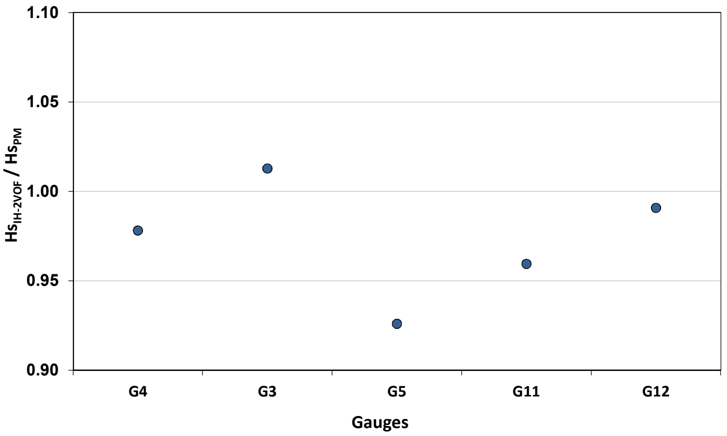

Figure 7: Values of H obtained with the model in each gauge for α=200 for PM2 and PM3 and α=1000 for PM1; β=0.5 for PM1 and PM2 and β=1.5 for PM3; and n=0.55 for PM1 and PM2 and n=0.60 for PM3.

The other sensitivity analysis that will be done before proper validation of the model is complete is a case with large overtopping. To get the volume of water that overtop the structure, the dimension of the mesh at the top of the crown wall is determinant to the results and should be as small as possible. This leads, as in the case mentioned before, to longer runs.

5. FURTHER DEVELOPMENTS

Within the scope of the research project entitled "DESTAQ – Development of velocity measurements advanced techniques for the Interaction analysis between detached breakwater and harbour structure", two numerical models – AMAZON, based on the non-linear shallow-water (NLSW) equations, and IH-2VOF, based on the Reynolds averaged Navier–Stokes (RANS) equations – are planned to be used to model the hydrodynamic processes around the Leixões harbour breakwaters (the existing and the submerged breakwater). In particular, the velocity field between the two breakwaters and the wave overtopping over the existing breakwater will be analyzed. The section of Leixões harbour reproduced in the physical model has four different porous media: three composed by artificial blocks and one by small rocks. The artificial blocks are: cubes (two layers, with different weight and slightly different geometry) and tetrapods.

The numerical models simulate the flow in a porous medium by the extended Forchheimer relationship, in which there are parameters that require calibration: the linear, α, and nonlinear, β, coefficients related to the linear and nonlinear drag forces, respectively. Additionally, for artificial blocks, porosity should be calibrated as well. All these constraints, as well as the fact that the effects of one porous medium are difficult to isolate from the others, made calibration especially difficult for this case study.

This paper presents the methodology that has been used to analyze the sensitivity of the IH-2VOF results to the porous media parameters that should be calibrated. The study started with the definition of several base values for the porous parameters. After that, for selected cases, the sensitivity runs consisted on changing, for each porous medium at a time, the value of each parameter one by one, maintaining the other values with a constant base value, to make it easier to analyze the influence of each parameter and of each porous medium on the results. The selected cases were those where the influence of one porous medium was expected to be larger than the others, making it possible to analyze the influence of each porous medium separately. The sensitivity study will give an indication on the relative importance of each porous medium parameter on the structure's behaviour. This information is very important to define the characteristics of the single porous medium that will be used in AMAZON to compute overtopping, which will allow a fast analysis for different wave conditions and geometry changes. Based on the results obtained in the sensitivity analysis, the IH-2VOF porous media parameters will be calibrated. After that the model will determine vertical and horizontal velocities in all the points of the mesh and can be applied and extended to situations not tested during the laboratory tests. First results obtained in this study are also presented in this paper in order to illustrate the described methodology. Based on these preliminary results, some values of the parameters were tested providing good agreement with the experimental results.

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