OVERTOPPING OF A POROUS STRCUTURE USING A SMOOTHED PARTICLE HYDRODYNAMICS NUMERICAL MODEL

D.R.C.B. NEVES [1], E. DIDIER [2], M.T. REIS [3] & M.G. NEVES [4]

[1] *Laboratório Nacional de Engenharia Civil - LNEC,*
Av. do Brasil, 101, 1700-066 Lisboa, Portugal. dneves@lnec.pt

[2] *Laboratório Nacional de Engenharia Civil - LNEC,*
Av. do Brasil, 101, 1700-066 Lisboa, Portugal. edidier@lnec.pt

[3] *Laboratório Nacional de Engenharia Civil - LNEC,*
Av. do Brasil, 101, 1700-066 Lisboa, Portugal. treis@lnec.pt

[4] *Laboratório Nacional de Engenharia Civil - LNEC,*
Av. do Brasil, 101, 1700-066 Lisboa, Portugal. gneves@lnec.pt

Abstract

This work presents the new developments on a SPH numerical model for studies on wave-structure interaction at the National Civil Engineering Laboratory (LNEC), Portugal. A piston-type wavemaker including active wave absorption and drift correction was implemented and a new technique based on a semi-automatic refinement of particles was applied to reduce the CPU time. Simulations were made regarding the study of the overtopping over the porous structure of the West breakwater of the Albufeira harbor in Portugal. Overtopping results were compared with the AMAZON and IH-2VOF simulations.

1. Introduction

Most of the maritime structures intend to prevent coastal hazards due to the wave action effects. The study regarding the response of these structures is therefore important to ensure both their stability and functionality. Wave-structure interaction generates very complex phenomena involving nonlinear processes, like wave propagation and transformation, run-up, wave breaking and overtopping. Coastal structures may have different structural characteristics: impermeable or porous structures, composed by artificial or rock blocks, with or without a wave return wall, etc. Numerical models, more or less complex depending on the approach and on the physical assumptions, allow simulating wave propagation.

Numerical modeling of the interaction among waves and coastal structures is a challenge due to the many non-linear phenomena involved. However, only few numerical models allow simulating the very complex phenomena of wave breaking, reflection and overtopping, and consequently forces at vertical structures. Those models are generally based on the Navier-Stokes equations and developed using an Eulerian approach. Among the existing models, one can highlight the three different types of models that are currently in development and validation at

LNEC: AMAZON model (Hu, 2000), based on the nonlinear shallow water equations; IH-2VOF model (Lara *et al.*, 2011), based on the RANS equations (Reynolds-Averaged-Navier-Stokes), and the SPH model (Monaghan, 1994) based on a Lagrangian method and the concept Smoothed Particle Hydrodynamics (SPH). The models AMAZON and IH-2VOF have already been successfully applied for wave-structure interaction studies: the first model is applied especially for the study of overtopping of impermeable structures but is being developed/validated for porous structures; the second model presents good results regarding studies of wave interaction with porous structures; the SPH model is under development and validation.

Recently, models based on Lagrangian methods, such as the SPH approach, have emerged. The method is based on the Navier-Stokes equations and a completely mesh-free technique. Monaghan (1994) demonstrated that SPH is a very promising alternative for modelling free surface flows and wave breaking. Different models have been developed, based on the SPH formulation of the Navier-Stokes equations, and there are many different numerical implementations. The SPH numerical model used and developed at LNEC is based on the original SPHysics model (Gómez-Gesteira *et al.*, 2008) and specially developed for studies of wave interacting with impermeable and porous structures. Promising agreement with experimental data has been obtained for both free surface elevation and overtopping discharge (Didier and Neves, 2009a, 2009b, 2010; Didier *et al.*, 2011). The present numerical model includes two specific developments: i) an active wavemaker absorption with paddle drift correction that allows the simulation of a semi-infinite numerical wave flume; and ii) a new technique of semi-automatic refinement by the division of fluid particles.

The work here presented is in the scope of the SPACE project "A Smoothed Particle Hydrodynamic model development and validation for coastal engineering applications" funded by the Portuguese Foundation for Science and Technology. The project partners are LNEC and the University of Algarve. The main objective of the project is to study and simulate numerically the overtopping phenomenon in porous structures. The case study is the West breakwater of the fishing harbor of Albufeira, in the South coast of Portugal. In this work the new implemented developments on the SPH model were tested for the case study structure and compared with the AMAZON and IH-2VOF results (Mariz *et al.*, 2012). A field campaign is being prepared in order to calibrate and validate the numerical models for the West breakwater of the Albufeira harbor.

Therefore in section 2 the case study and the project SPACE are described. The fundamental principle of the SPH method is explained in section 3 and the new improvements on the SPH model are described. In the 4th section results are presented and compared with the AMAZON and the IH-2VOF models. The conclusions and future work are presented in the last section of this work.

2. SPACE Project

The main objectives of the SPACE project are the development of the numerical SPH model, based on the Lagrangian form of the Fluid Mechanics equations, for applications requiring the interaction of the waves with impermeable and porous coastal structures (vertical breakwaters and rubble-mound breakwaters made with rock or with artificial blocks), more specifically to calculate the forces on the structure and the overtopping discharge.

The coastal structure studied within the SPACE project represents the most exposed breakwater of the Portuguese fishing harbour of the Albufeira village (West breakwater).

For this purpose, field measurements will be performed by the University of Algarve at the West breakwater of Albufeira Harbor (Algarve, South coast of Portugal) (Figure 1).

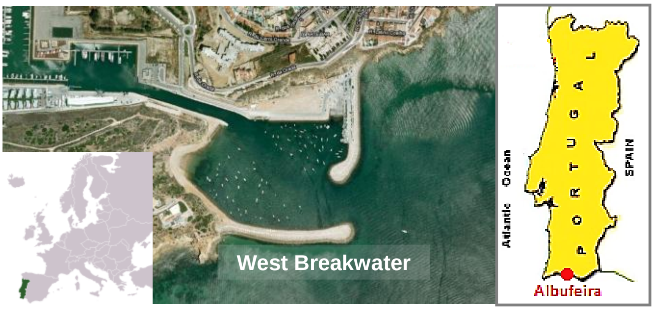

Figure 1 – Location of the West breakwater of the Albufeira harbor

The breakwater is protected by 2 rock armour layers of 90-120kN on a 2:3 slope, down to -4.0m (CD). It has a 5.7m wide crest berm at +7.0m (CD) and a 3.0m wide concrete platform with its crest at +6.5m (CD). Figure 1 presents a view of Albufeira fishing harbor. The study area is under a mesotidal regime with tide amplitude between 1.3 and 2.8m, for both neap and spring tide, reaching maximum levels close to +3.8m (CD). The main wave direction is from W-SW (71% of the year). The main storms (Hs > 3.0m) are swell from SW and storms with Hs about 4.0m occur at least once a year.

In 2012 a field campaign is planned for the presented breakwater. Contrary to the programme of the SPACE project, the field measurements are not yet collected due to the atypical maritime conditions of the 2011-2012 Winter. However, by now the breakwater is fully-equipped and a protocol was established in case of an eminent overtopping event. Topographic and bathymetric surveys have been already made to the -12m (CD) contour. Pressure transducers, current meters and video monitoring will allow measurements of (i) waves (both offshore and near the wave breaking); (ii) run-up and overtopping (flow and level); (iii) wind intensity and direction. The measurements will provide data to validate the numerical models and to analyse scale effects from the physical modelling to be performed at LNEC.

In this work, regarding the study of the SPH numerical model for the proposed structure (sections 3 and 4), for a tide level of +3.5m (CD) (corresponding to a spring tide in Albufeira), an incident regular wave period of T=12s and a wave height of H=4m were selected, to represent a clear scenario of an overtopping event.

The SPH model was developed regarding the application to the case study, by implementing a piston-type wavemaker with an absorption and drift correction system for the reflected waves, allowing the modeling of a semi-infinite flume, and consequently, suppressing the reflection problems in the calculations domain. This enabled the increase of the simulation time, resulting on a fair statistical analysis of the results. Also, in order to model real coastal structures it is necessary to consider the porosity of the structure, made by rock or artificial blocks. Thus, the possibility of placing cubic blocks was implemented in the SPH code, in order to directly model the porous layers and the flow inside and outside the layers (i.e. between the blocks). Moreover a semi-automatic refinement was implemented by division of fluid particles, with the objective of improving and decreasing the calculation time, whilst maintaining the best possible results.

3. SPH numerical model

The above work here presented aims to take a step forward in validating the SPH model for porous structures, which can be simulated using a porous media model. However, for coastal structures with concrete blocks and rock-fill armour, with a typical porosity of 35-40%, SPH enables the simulation of the flow inside the armour layer and around each block. In this case, it becomes necessary to use sufficiently small particles comparing with the average spacing between the blocks of the armour layer. In the present study, only blocks of the armour layer are modelled and the under layer and the breakwater core are considered impermeable.

3.1. SPH method

The SPH method (Monaghan, 1994) is based on a Lagrangian formulation of Navier-Stokes equations. It is a mesh free technique which allows modeling fluid particle trajectories. Numerically, the interaction between the particles is ensured by an interpolation function, the kernel (Liu, 2003).

Lagrangian Navier-Stokes equations are transformed into SPH forms, by integral equations using integral interpolants, which allows to approximate any function *A(r)* by:

$$A(r) = \int_{\Omega} A(r')W(r - r', h)dr' \quad [1]$$

where r is the vector particle position, W is the weighting function, h is the smoothing length. The kernel allows determining the interaction among neighboring particles included in the influence domain, a compact support within a circular region determined by a radius of $2h$, controlled by the smoothing length h, typically higher than the initial particle spacing, d_0.

The two-dimensional SPH equations are based on the Lagrangian formulation of the conservation of momentum and continuity:

$$\frac{dv}{dt} = -\frac{1}{\rho}\nabla P + \Pi + g \quad [2]$$

$$\frac{1}{\rho}\frac{d\rho}{dt} = -\text{div } (v) \quad [3]$$

where t is the time, Π represents the viscous terms, g = (0, -9.81) ms^{-2} is the acceleration of gravity, v, P and ρ are, respectively, the velocity, pressure and density.

The standard SPH formulation (Monaghan, 1994), in which the fluid is considered slightly compressible, is used and the pressure is calculated by an equation of state (Batchelor, 1974):

$$P = B\left[\left(\frac{\rho}{\rho_0}\right)^{\gamma} - 1\right] \quad \text{with} \quad B = \frac{c_0^2\rho_0}{\gamma} \quad [4]$$

with γ=7, ρ_0 the reference density and c_0 the sound speed.

The trajectories of the particles are obtained from the following relationship:

$$\frac{dr}{dt} = v \quad [5]$$

LNEC's SPH model, based on the SPHysics code (Gómez-Gesteira *et al.*, 2008; SPHysics code v1.4, 2008), has been developed for solving coastal engineering problems and modeling complex free surface flows and wave interacting with coastal structures.

3.2. Implemented innovations on LNEC's SPH model

Three main innovations on the SPH code were implemented and tested in the present work: (i) the active wavemaker absorption that allows simulating a semi-infinite flume, (ii) the correction of the wavemaker drift, and iii) the new semi-automatic refinement by division of fluid particles, in order to decrease the computational time without loss on results accuracy.

3.2.1. Active wavemaker absorption

In order to simulate a semi-infinite numerical wave flume, it is necessary to use active wavemaker absorption, instead of simple wavemaker (Didier and Neves, 2012). This model enables to obtain longer time series of free surface elevation, overtopping and forces for calculating correctly statistical data.

In the original SPHysics model, wave generation is performed moving the solid particles of the wavemaker boundary, similar to the experimental flume. The wavemaker movement is simulated in the numerical model through the position $X_b(t)$ and velocity $U_b(t)$ of the solid particles constituting the wavemaker, deduced from the linear wave theory and, for a regular wave, given by the following relations:

$$X_b(t) = X_b(t_o) + A_b \sin(2\pi t / T) \;,\; U_b(t) = 2\pi A_b / T \cos(2\pi t / T) \qquad [6]$$

where T is the incident wave period, A_b the wavemaker amplitude, $X_b(t_o)$ the initial position of the wavemaker and t the time.

Active wavemaker absorption followed the same procedure as in physical flumes: the numerical wavemaker is equipped with a control system for simultaneous wave generation and active wave absorption. The methodology proposed by Shäffer and Klopman (2000) is applied. This methodology is also applied with success in IH-2VOF code (Lara *et al.*, 2011).

The target wavemaker position, $X_b(t)$, is corrected in real time in order to absorb outgoing waves and to avoid reflection at the wavemaker. The position of the wavemaker is obtained through the velocity corrections of the wavemaker motion, and comparing the target-free surface, η_{target}, to the free surface recorded in front of the wavemaker, η_{SPH}. The velocity correction owing to absorption of the reflected wave, U_R, can be written as follows:

$$U_R = \eta_R (g/h)^{1/2} \quad \text{with} \quad \eta_R = \eta_{target} - \eta_{SPH} \qquad [7]$$

where g is the gravity acceleration and h is the water depth.

To obtain the wavemaker position, velocity has to be integrated considering both the target velocity, U_{target}, calculated using Eq. [6], and the velocity correction, U_R,

$$X_b(t) = X_b(t_o) + \int_0^t \left(U_{target} + U_R\right) dt \qquad [8]$$

The corrected wavemaker velocity, $U_b(t)$, is obtained by the relation

$$U_b(t) = U_{target} + U_R \qquad [9]$$

3.2.2. Correction of the wavemaker drift

A recent change in the numerical model regarding the active wavemaker absorption technique consisted in correcting the wavemaker drift observed in some numerical applications. Numerically, wavemaker drift correction is similar to the one used in an experimental flume. The drift correction is performed in real time in order to maintain the mean position of the paddle, which can be different from the initial position, $X_b(t_0)$.

The correction is made by adding a correction velocity $U'_b(t)$ to the velocity calculated in the active wavemaker absorption $U_b(t)$ Eq. [9].

$$U_b(t) = U_{target} + U_R + U'_b \qquad [10]$$

Figure 2 presents the wavemaker position over time with and without drift correction. The implemented correction technique eliminates the drift by adjusting the paddle position. Without the wavemaker correction drift, the paddle is deviating from its initial mean position. With the wavemaker drift correction, the paddle stays on a mean position very close to its initial mean position.

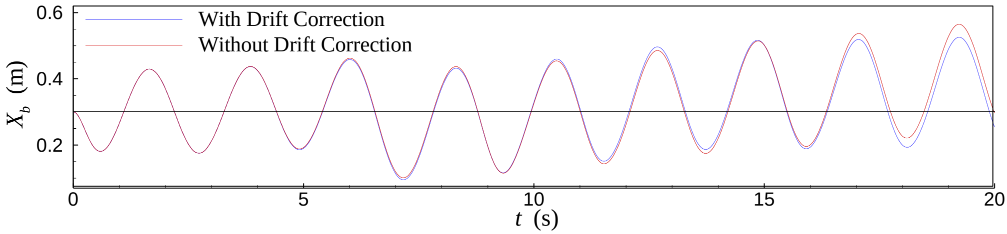

Figure 2 – Paddle position over time with and without wavemaker drift correction

3.2.3. Semi-automatic refinement technique

The developed SPH model enables the division into 2, 3 or 4 smaller particles, at any time during the calculations, allowing the refinement when it is most needed (Figure 3). The refinement technique was implemented with the objective of decreasing the calculation time whilst maintaining the same quality of the results.

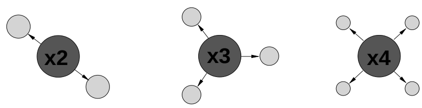

Figure 3 – Division of the particles into 2, 3, or 4 smaller particles

This technique allows SPH simulations with a coarse resolution, producing relatively short CPU time in order to model the transient part of the flow, i.e. before stabilizing the interaction between the incident and reflected waves by the structure. After obtaining this flow stabilization the technique is applied in order to split all the fluid particles in the computational domain (Figure 4), thereby increasing the resolution in order to obtain more accurate results. This technique is to be applied for studies regarding tests on a semi-infinite wave channel, where the transient flow is not relevant to the results analysis.

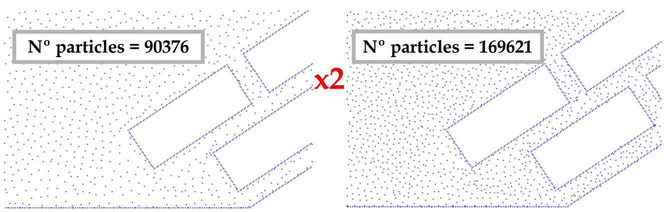

Figure 4 – Division of the fluid particles into 2 smaller particles

4. Results

The numerical simulation of the wave overtopping of a porous structure is a very challenging problem due to the complex non-linear phenomena that occur during this event: wave propagation in the vicinity of the structure, wave breaking, run-up, reflection, interaction between the incident wave and the reflected wave and overtopping.

4.1. Numerical Implementation

Numerical simulations are performed using a quadratic kernel, the predictor-corrector scheme for time integration, a Sub-Particle Scale viscosity (based on Large Eddy Simulation and Sub-

Grid Scale model), and the repulsive boundary condition, which prevents a water particle from crossing a solid boundary. No density renormalization of fluid particles was applied in the present simulations. Initially, water particles are placed in the flume using a Cartesian distribution, i.e. particles are regularly distributed, with spacing between particles defined by *do*. Velocity is zero and pressure is hydrostatic.
SPH simulations and the computational domain were generated at a scale of 1:30 (Figure 5). Numerical simulations of wave interacting with the Albufeira breakwater were carried out for an incident regular wave with period T=12s, wave height H=4m and water depth h=9.05m. The bottom profile and structure dimensions are indicated in Figure 6.

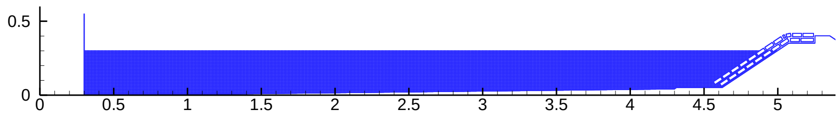

Figure 5 – Computational domain (scale 1:30)

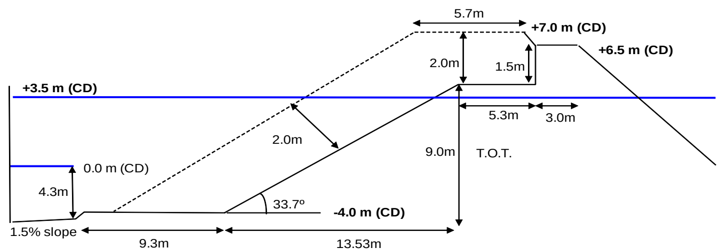

Figure 6 – Bottom and structure dimensions (prototype scale)

The SPH model allows the simulation of the water flow between the blocks that take part of the porous layer. It becomes necessary to use sufficiently small particles compared with the average spacing between the blocks of the armour layer. In the present study, only blocks of the armour layer are modelled and the under layer and the breakwater core are considered impermeable. The porous layer, as indicated in Figure 6, had 2m width. The porosity was defined as follows:

$$n = (A_{total} - A_{blocs}) / A_{total} \qquad [2]$$

The tested porosities were 30%, 35% and 40% and a minimum of 3 particles was defined as the minimum space between blocks. These porosities were chosen in order to compare the SPH model results with those from the AMAZON and the IH-2VOF models.
The studied breakwater has a first armour layer with blocks of the same dimensions and fixed uniformly from the crest to the bottom. It was decided to test a 22 block structure, also with uniformly placed blocks and with a nominal diameter, D50. Figure 7 shows the blocks in the SPH model and the rocks in the prototype.

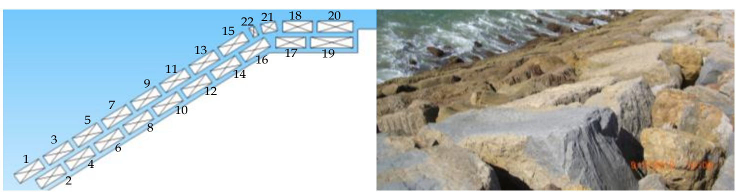

Figure 7 – SPH blocks (on the left) and blocks of prototype structure (on the right)

4.2. Free Surface

Figure 8 shows the time series of free surface elevation obtained with the IH-2VOF and the SPH models. IH-2VOF and SPH results are quite well aligned, indicating that SPH simulates correctly the wave propagation. The differences between the two model results are explained by the different wave generation methods: SPH generates the waves with a wavemaker movement and IH-2VOF imposes an incident 2nd order Stokes wave in a fixed boundary. These wave generation methods drive to different energy distributions between the fundamental frequency and the harmonics. Also the differences in phase can explain the results. It can be seen that porosity does not modify significantly free surface elevation.

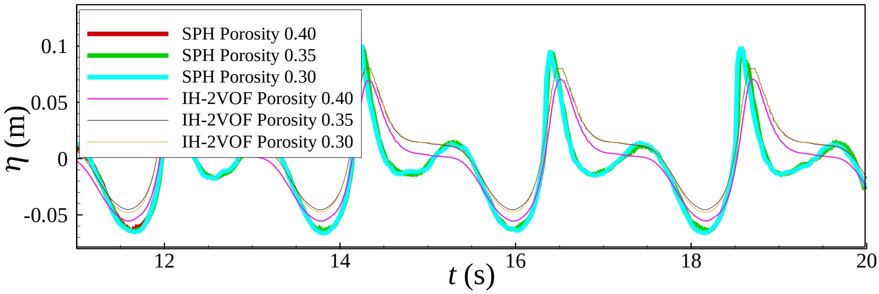

Figure 8 – Free surface elevation from the SPH and the IH-2VOF models at x=4.08m in front of the structure (scale 1:30)

4.3. Overtopping

Figure 9 shows the time series of overtopping volume and presents the expected results from the SPH simulations, with bigger porosities producing less overtopping.

Table 1 indicates the three different SPH simulations: two different resolutions of d_0, 0.00396m and 0.0028m, from "SPH(d)" and "SPH(d/2)" respectively, and another one using the semi-automatic refinement "SPH(d/2) REF", where simulation until 20s was performed with d_0=0.00396m and from 20 to 30s with d_0=0.0028m.

Table 2 presents the comparison of the mean overtopping discharge for three porosities between AMAZON, IH-2VOF and three SPH resolutions. SPH results present approximately 2.5 to 4 times greater values of mean overtopping discharge than those of AMAZON and IH-2VOF. This can be partly explained by the wave heights obtained with the SPH model (Figure 8). However the tendency regarding the porosity is similar. Concerning the porosity influence in the overtopping results, the AMAZON and the IH-2VOF models show a significant change with the porosity, unlike the SPH results that present minor changes. This SPH behavior concerning the porosity is probably due to lack of resolution in the simulations that prevents the free dynamics of the particles inside the porous layer and induce a reduction of porosity: less resolution in the SPH model produces less permeability in the porous layer.

In order to assess the effect of the resolution and refinement on the SPH model, Table 3 shows the relative error between SPH(d/2) REF and the two other simulations. This comparison proved to be greater between SPH(d/2) REF and SPH(d/2) than with SPH(d), except for the porosity 0.35. However, all the SPH values for the different simulations are close and no further conclusion can be taken. Further analysis will be presented in future works.

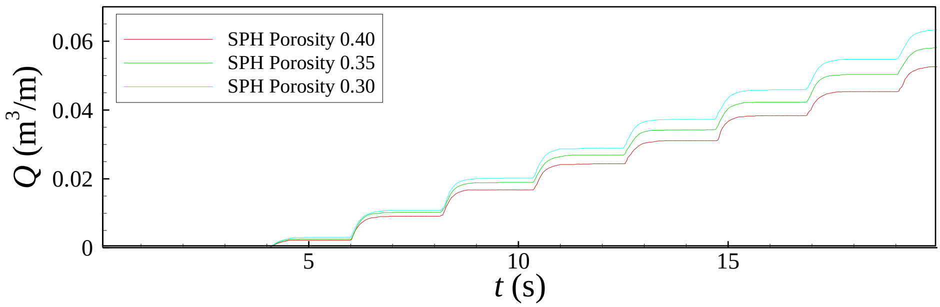

Figure 9 – Wave overtopping results obtained with the SPH model for three porosities (d_0=0.00396m)

Table 1. Resolution of SPH simulations

SPH simulations	d_0 (m)	Refinement
SPH(d)	0.00396	No
SPH(d/2)	0.0028	No
SPH(d/2) REF	0.00396 and 0.0028	Yes

Table 2. Mean overtopping discharge obtained with IH-2VOF, AMAZON and SPH models for three porosities and three types of refinement for SPH

Porosity (n)/Q ($m^3/s/m$)	AMAZON	IH-2VOF	SPH(d)	SPH(d/2)	SPH(d/2) REF
0.3	0.208	0.219	0.518	0.544	0.489
0.35	0.146	0.167	0.471	0.512	0.477
0.4	0.095	0.121	0.428	0.474	0.415

Table 3. Mean overtopping discharge obtained with the SPH model and relative error (%)

	n=0.30		n=0.35		n=0.40	
SPH(d/2) REF	0.489	Relat. error (%)	0.477	Relat. error (%)	0.415	Relat. error (%)
SPH(d/2)	0.544	11.16	0.512	7.23	0.474	14.21
SPH(d)	0.518	4.78	0.471	8.03	0.428	9.70

5. Conclusions

New improvements were applied in the SPH model code regarding the overtopping calculations for porous maritime structures. The active wavemaker absorption with the drift correction and the semi-automatic refinement technique were successfully implemented and tested in LNEC's SPH numerical model.

The first numerical results from the SPH model obtained within the scope of the SPACE project were presented. The results of the SPH model show some differences with results obtained from AMAZON and IH-2VOF. With the intention of supporting and validating the results of the numerical models, the planned experimental results of the SPACE project are needful. The new improvements in the SPH model are currently in development and more enhancements will be made to achieve better results.

Physical model tests in a wave flume are currently being undertaken and will provide values to compare with the numerical results enabling the model validation and calibration.

The first field campaigns in Portugal for the measurement of wave overtopping in a harbor breakwater were presented and will be carried out in winter 2012.

Acknowledgments

The authors gratefully acknowledge the financial support of the Portuguese Foundation for Science and Technology, through project SPACE "A Smoothed Particle Hydrodynamic model development and validation for coastal engineering applications", PTDC/ECM/114109/2009.

References

Batchelor GK (1974). 'Introduction to Fluid Dynamics'. *Cambridge Univeristy Press*, UK.

Didier E and Neves MG (2009a). 'Wave overtopping of a typical coastal structure of the Portuguese coast using a SPH model', *J.Coastal Research*, SI 56, pp. 496-500.

Didier E and Neves MG (2009b). 'Coastal flow simulation using SPH: Wave overtopping on an impermeable coastal structure', *Proc 4th ERCOFTAC SPHERIC workshop*, pp. 357-364, Nantes, France.

Didier E and Neves MG (2010). 'A Lagrangian Smoothed Particle Hydrodynamics – SPH – method for modelling waves-coastal structure interaction', *Proc CFD2010 ECCOMAS*, Lisbon, Portugal.

Didier E, Martins R, Neves MG and Vasco JRG (2011). 'Interaction between wave and coastal structure: validation of two Lagrangian numerical models with experimental results', *Proc. MARINE 2011*, Lisbon, Portugal.

Didier E and Neves MG (2012). 'A Semi-Infinite Numerical Wave Flume using Smoothed Particle Hydrodynamics', *Int. J. of Offshore and Polar Eng.*, 22, Nº2, pp. 193-199.

Gómez-Gesteira M, Rogers BD, Dalrymple RA, Crespo AJC and Narayanaswamy M (2008). 'User Guide for the SPHysics Code v1.4', Manchester, UK.

Hu K (2000). 'High-Resolution Finite Volume Methods for Hydraulic Flow Modelling', PhD Thesis, Manchester Metropolitan University, UK.

Lara JL, Ruju A and Losada IJ (2011). 'Reynolds averaged Navier-Stokes modelling of long waves induced by transient wave group on a beach', *Proc. R. Soc. A*, 467, pp. 1215-1242.

Liu GR (2003). 'Mesh free methods. Moving beyond the finite element method'. CRC press.

Mariz S, Patrício T, Reis MT, Silva AP, Didier E and Hu K (2012). 'Cálculo do galgamento no quebra-mar poente do porto de pesca de albufeira: aplicação dos modelos AMAZON e IH-2VOF', *4th MEFTE* 2012, Lisbon, Portugal.

Monaghan JJ (1994). 'Simulating free surface flows with SPH', *J. Comp. Physics*, 110, pp. 399-406.

Schäffer H and Klopman G (2000). 'Review of multidirectional active wave absorption methods', *J. Waterw. Port. Coast. Ocean Eng.*, 126, pp. 88–97.

SPHysics code v1.4 (2008). '*SPHysics homepage*', http://wiki.manchester.ac.uk/sphysics.