Coastal flow simulation using SPH: Wave overtopping on an impermeable coastal structure

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***Abstract*— Wave overtopping is a violent natural event that involves highly complex phenomenon such as large deformation of free surface, turbulence and eddy vortices, strong interaction between the wave and the structure. Models based on Smoothed Particle Hydrodynamics (SPH), that used a mesh-free technique, are an option to address wave overtopping and other phenomena involved on the interaction between waves and coastal structures. In the present paper, SPHysics model is validated and applied for wave propagation and wave overtopping of an impermeable seawall. Validation and convergence study is carried out considering several parameters such as the initial particle density and the ε_{XSPH} parameter. Free surface elevation in several gauges and overtopping discharge over the structure are analyzed and compared to experimental data and other numerical results. A very satisfactory agreement is obtained with experimental measurements. Finally, the numerical model is applied for modelling wave propagation with breaking and overtopping of an impermeable sea wall coastal defence structure, a common structure employed at the Portuguese coast. Numerical results are compared with experimental data from model scale tests carried at the National Civil Engineering Laboratory (LNEC). Good agreement is obtained for both free surface elevation and overtopping discharge over the structure.**

I. INTRODUCTION

Sea walls are structures that allow the protection of coastal areas from the wave attack. In the project of those structures, wave-structure interaction study should be made to define the viability and efficiency of the structure, namely the overtopping discharge and the forces applied on the structure. Wave-structure interaction generates very complex phenomena involving nonlinear processes, like wave propagation and transformation, run-up, wave breaking, and overtopping. Coastal structures could have different structural characteristics: could be impermeable or porous structures, composed by artificial blocs, be an arc crown wall structures, etc.

Numerical models, more or less complexes depending on the approach and on the physical assumptions, allow simulating near shore transformation and propagation of waves.

The models based on the nonlinear Boussinesq equations, such as COULWAVE [1], give good predictions comparing with field data and laboratory physical modelling. However, it does not model the breaking wave and highly nonlinear processes that occur between waves and coastal structures, such as breaking and overtopping.

Some numerical models allow simulating these very complexes phenomenon. Those models are generally based on fluid dynamic equations, i.e. the Navier-stokes equations, and developed using an Eulerian approach. Numerical simulation of free surface flows is treated using the Volume of Fluid (VOF) approach, such as the Reynolds Average Navier-Stokes (RANS) model COBRAS-UC [2]. However the recent advances on Smoothed Particle Hydrodynamics (SPH) models show that Lagrangian method is a very promising alternative approach to simulate wave breaking and overtopping due to its completely mesh-free technique.

In the present paper, SPHysics numerical model [3] is validated for wave propagation through an impermeable coastal structure for two different cases. In the first case, wave overtopping discharge over an impermeable sea wall defence structure is simulated. Numerical results of SPHysics model are compared with results from a SPH model [4], from Eulerian numerical models [5] and with experimental data obtained by Saville (from Shao et al. [4]). Validation of the numerical model for this very complex phenomenon is performed studying the influence of various parameters, such as the initial density of particles, the viscosity model (artificial [6] and SPS [7]) and the ε_{XSPH} parameter of the XSPH variant of Monaghan [8] that allows correcting the velocity of a particle. In the second case, SPHysics model is applied for modelling wave propagation with breaking and overtopping of an impermeable sea wall coastal defence structure, a common structure employed at the Portuguese coast. Numerical results of free-surface deformation at several positions along the flume and overtopping discharge are compared with experimental data from model scale tests obtained at the National Civil Engineering Laboratory (LNEC) in the framework of the Composite Modelling of the Interactions between Beaches and Structures (CoMIBBs) project – HYDRALAB III European project [9].

II. Numerical model

SPHysics is an open-source Smoothed Particle Hydrodynamics program developed jointly by researchers of several Universities [3]. The model is inspired by the formulation of Monaghan [6]. The fluid in the standard SPH formalism is treated as weakly compressible. The model presents a modular form and a variety of features are available to choose different options, like: 2D and 3D model, time scheme (Predictor-Corrector or Verlet algorithm), constant or variable time step, various kernels, viscosity models (artificial, laminar and Sub-Particle Scale turbulence model), density filter (Shepard or MLS), and solid boundary conditions (dynamic boundaries, repulsive forces). Detail of numerical implementation and references are available at the website of SPHysics [3].

For the present numerical simulations, the quadratic kernel [10] is used to determine the interaction between the particles. The fluid is treated as weakly compressible which allows the use of an equation of state to determine fluid pressure. The relationship between the pressure and the density was assumed to follow the equation of state. The compressibility is adjusted to slow the speed of sound so that the time step in the model, based on the sound velocity, is reasonable. Integration in time is performed by the Predictor-Corrector model using a variable time step. The repulsive boundary condition, developed by Monaghan [8], is used and allows preventing a water particle crossing a solid boundary. Variable time step is used to ensure the CFL condition.

Simulations are carried out considering various options for the numerical parameters for studying their influences on results:

- Sub-Particle Scale – SPS – turbulence model [7] or artificial viscosity model [6]. Artificial viscosity model required to define the empirical coefficient, usually taken as 0.01-0.1. Padova [11] shows that small empirical coefficient α allows better agreement with experimental measurements.
- Particles are usually moved using the XSPH variant due to Monaghan [12], with ε_{XSPH}=0.5 (values ranged between 0 and 1). The method is a correction for the velocity of a particle, which is recalculated taking into account the velocity of that particle and the average velocity of neighbouring particles.

Computations are carried out with several initial particles spacing to study the convergence behaviour of free surface and overtopping discharge.

III. Convergence analysis and validation

The numerical simulation of the overtopping of a seawall is a very challenging problem due to the complex phenomenon that occur during this event: wave propagation and transformation in the nearshore region, wave breaking, run-up, reflection, interaction between the incident wave and the reflected wave and overtopping. Numerical simulations of wave overtopping over a smoothed and impermeable sloping seawall are carried out to validate the SPHysics model. Results of average overtopping discharge obtained with SPHysics model are compared with other numerical results and experimental measurement.

Data of wave overtopping of sea walls were collected by Saville in a wave flume using regular waves (from Shao et al. [4]). Several seawall profiles, wave heights, wave periods and water depths were tested. Here, just one of those configurations is simulated to validate SPHysics model and to study the convergence behaviour.

Figure 1 shows the schematic profile of the tested sea wall, where *h*, *ds* and *Rc* are the water depth at the seaward boundary, the water depth at the toe of the structure and the crest level of seawall above the still water surface. The beach and the seawall slopes are 1:10 and 1:3, respectively. The simulation is carried out for *h*=3.0m, *ds*=0.75m and *Rc*=0.5m. The regular wave period is *T*=4.73s and the wave height *H*=1.0m. The wave length at the seaward is 23.4m. The paddle at the left boundary moves harmonically with an amplitude equal to 0.624m. However, it is not designed to absorb the reflected waves from the downstream.

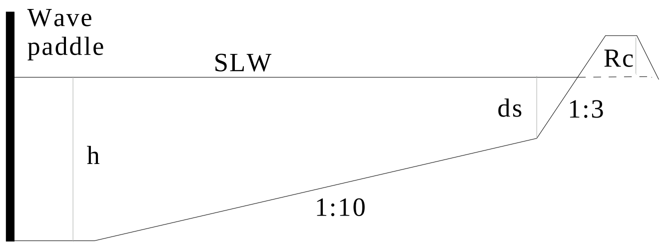

Figure 1. Schematic profile of the computational domain.

To calculate the overtopping discharge, a particle counter is located at the beginning of the seawall crest. A mass and density are associated to the water particles, making easy to define the total overtopping volume and the average discharge per wave. Average overtopping discharge is counted between the 3rd and 5th waves when flow structure interaction is relatively periodic and before re-reflexion of wave on the wave paddle.

Free surface elevation is compared in three gauges located at 0.0m, 6.5m and 14.5m, respectively gauge 1, 2 and 3, from the beginning of the beach.

A. Influence of initial particle spacing

For the computational domain, a uniform particle spacing is used, varying from *dx*=*dy*=0.03m to 0.15m. The number of particles varies from 56287 to 2509. SPS turbulent model and ε_{XSPH}=0.0 are used for simulations. Shao et al. [4] used only a uniform particle spacing with *dx*=*dy*=0.1m, that corresponds to 5390 particles.

Figures 2, 3 and 4 show the free surface elevation at the three gauges, 1, 2 and 3. It can be noted that wave transformations occur during the propagation over the beach profile due to the nonlinear processes. Analysing Figure 2 it is possible to see that the difference between wave crests, due to the particle density, is larger than the difference between wave through. Differences up to 16% are found for wave height at the wave crest and around 7% for wave through between the larger and smaller initial particle density. In Figure 4, nonlinear effect can be observed and differences between wave crests and through increase. However, for initial particle density with spacing 0.03 to 0.05, wave shape presents similar trend. Differences at gauge 1 and 3, with particle spacing between 0.03 and 0.05, are only around 2% and 3%, respectively.

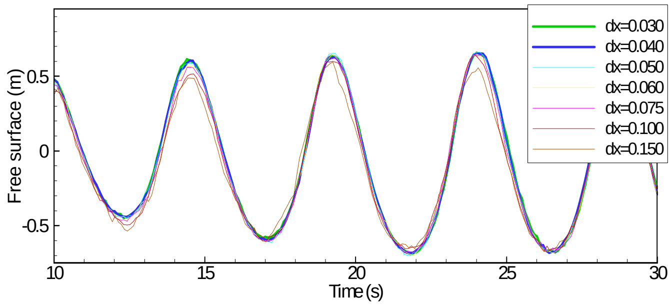

Figure 2. Free surface elevation at gauge 1, x=0.0m.

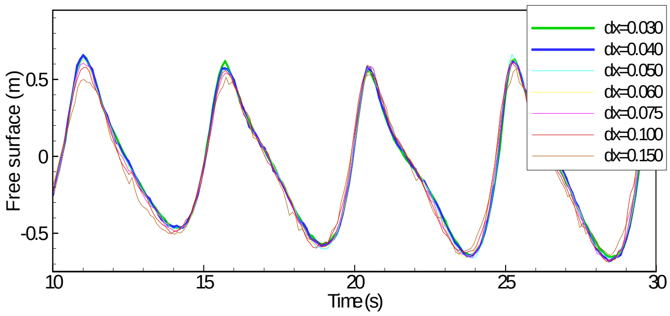

Figure 3. Free surface elevation at gauge 2, x=6.5m.

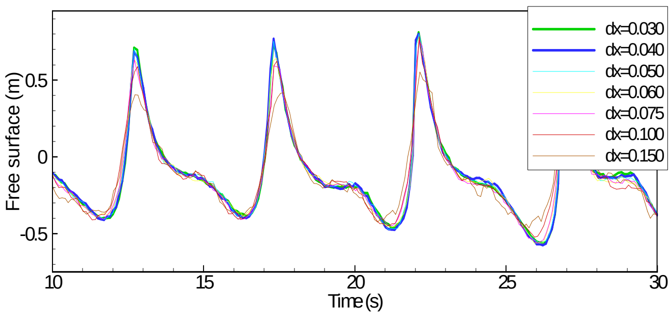

Figure 4. Free surface elevation at gauge 3, x=14.5m.

Figure 5 presents the total overtopping discharge obtained during the simulation. Overtopping discharge presents the same trend for all initial particle densities and overtopping volume increases from wave to wave. However the overtopping volume value varies with the particle density. Eventhough, as it is possible to see, convergence is not very clear. It should be pointed out that overtopping is a very sensitive parameter and strongly depends on the wave breaking and other nonlinear processes that occur in front of the sea wall structure.

Figure 6 shows the total overtopping volume calculated at wave 3 and 6. For low particle density the calculated overtopping volume is underestimated and the error, compared with larger particle density, is around 30% lower. For the particle density that corresponds to particle spacing from 0.03 to 0.05, differences on calculated overtopping volume are smaller and equal to 7% and 4% for wave 3 and 6, respectively. It seems that convergence is approximately obtained with initial particles spacing smaller than 0.06m. However it is necessary to confirm this tendency using a larger particle density.

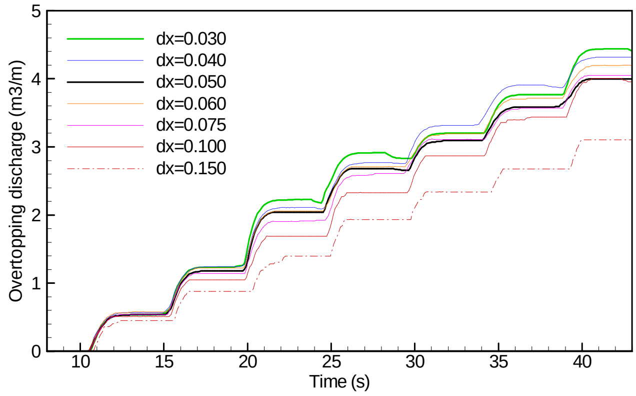

Figure 5. Overtopping discharge for various initial particle density.

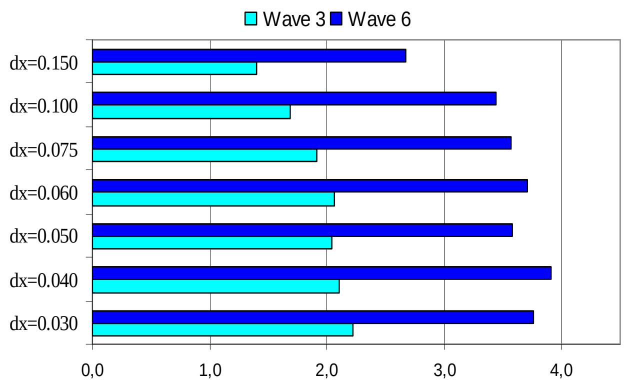

Figure 6. Overtopping volume discharge at waves 3 and 6, for different initial particle density.

B. *Influence of XSPH correction parameter*

Particles motion is usually performed using the XSPH variant of Monaghan. Influence of XSPH parameter, ε_{XSPH}, is studied considering initial particle spacing dx=dy=0.05m and the SPS turbulent model.

Figures 7 and 8 show the free surface elevation at gauge 2, for the time interval of 0s to 45s and 65s to 100s, respectively, and for XSPH parameters from 0.0 to 0.5. Free surface elevation is the same for the first waves but discrepancy increases during the simulation. Significant differences are found in function of the ε_{XSPH} parameter value. For the usual value ε_{XSPH}=0.5, free surface elevation presents a very unusual behaviour, since free surface elevation decrease dramatically during the simulation, until the program stops after some iterations. As ε_{XSPH} value tends to zero, discrepancies of free surface elevation decreases.

For value of ε_{XSPH}=0.5, water particles cross the solid boundary due to the presence of structures with high vorticity intensity and velocity near the solid slope boundary. Figures 9 and 10 show, for the same time, the position of the particles for ε_{XSPH}=0.5 and ε_{XSPH}=0.0 respectively. As expected, the behaviours are very different, since in the case of ε_{XSPH}=0.5 the mean water level decrease due to the particles that cross the solid boundary and wave breaking occurs far from the sea wall since the water depth is smaller. When the correction XSPH is zero, ε_{XSPH}=0.0, particles do not cross the solid boundary and the results are very different.

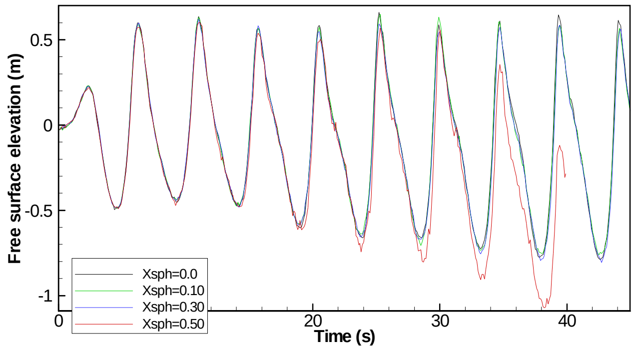

Figure 7. Free surface elevation at gauge 2, *x*=6.5m, for various XSPH parameters between time 0s to 45s.

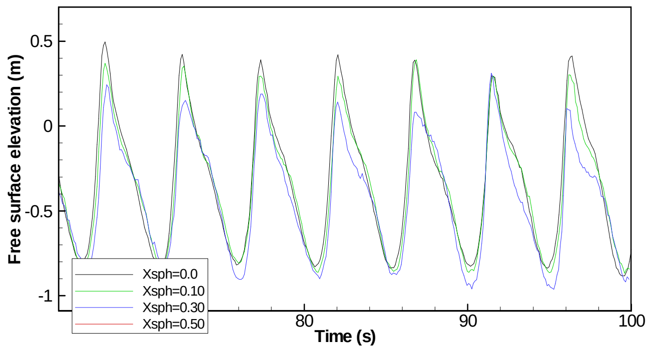

Figure 8. Free surface elevation at gauge 2, *x*=6.5m, for various XSPH parameters between time 65s to 100s.

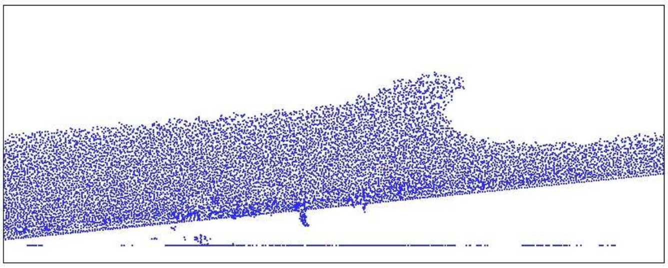

Figure 9. Particles crossing the solid boundary for XSPH parameter ε_{XSPH}=0.5.

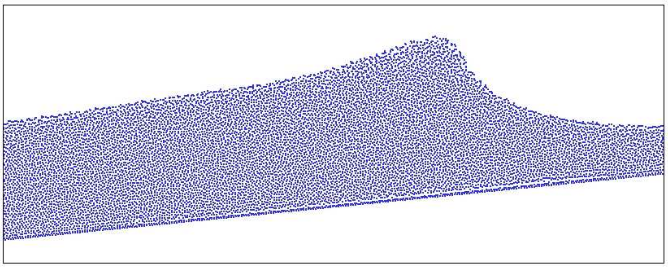

Figure 10. Particles not crossing the solid boundary for XSPH parameter ε_{XSPH} =0.0.

C. *Influence of the viscosity model*

Sub-Particle Scale (SPS) approach for modelling turbulence, first described by Gotoh et al. [7], is used and compared with the artificial viscosity (AV) model proposed by Monaghan [6], with the empirical coefficient α varying from 0.01 to 0.10. Initial particle density corresponds to particle spacing *dx*=*dy*=0.05m.

Figure 11 presents the total overtopping discharge during the simulation. Figure 12 shows the overtopping discharge volume at waves 3 and 6. As expected, there are differences between SPS approach and artificial viscosity model increases as the empirical coefficient α increases. The model is too dissipative and the overtopping discharge accuracy decreases. This result is confirmed by Padova [11] that shows that better agreement is obtained between numerical results and experimental measurements with smaller empirical coefficient values.

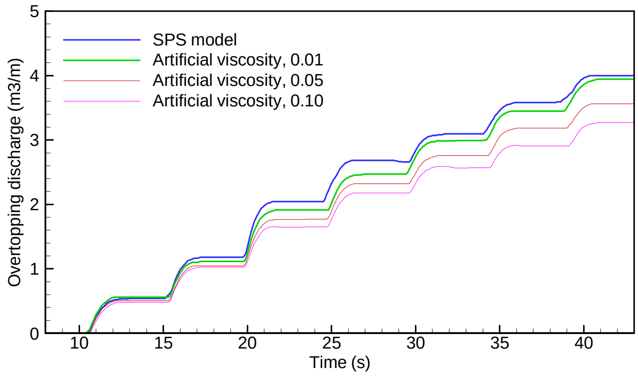

Figure 11. Overtopping discharge for SPS approach and artificial viscosity model for various empirical coefficient α.

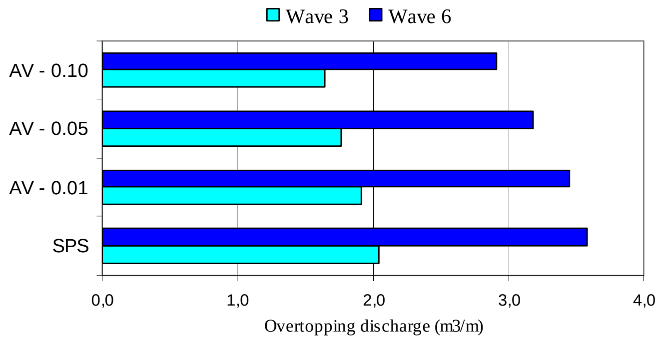

Figure 12. Overtopping discharge volume: comparison between SPS approach and artificial viscosity model for various empirical coefficient from α=0.01 to 0.10, at wave 3 and 6.

Figures 13 and 14 present the free surface elevation at gauges 1 and 3. As it is seen the wave shape presents the same trend for the four cases. Differences are relatively small between SPS and artificial viscosity models at gauge 1. However, when nonlinear effects increase due to the decrease of the water depth, wave height increases and differences appear for these steepness waves. An error of 13% is found for the wave crest between the SPS results and artificial model with the smaller empirical parameter, α=0.01.

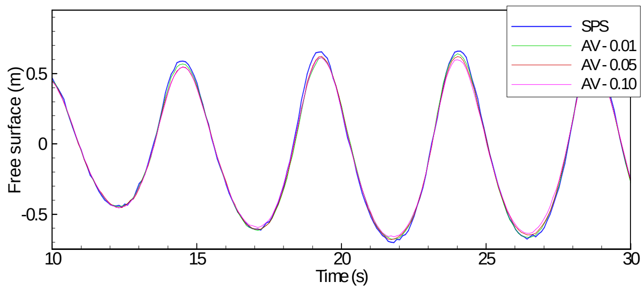

Figure 13. Free surface elevation at gauge 1, for SPS model and artificial viscosity model for various empirical coefficient α.

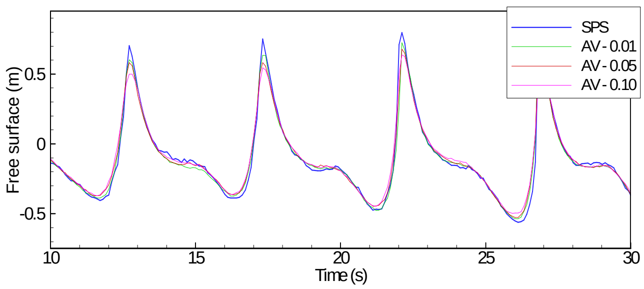

Figure 14. Free surface elevation at gauge 3, for SPS model and artificial viscosity model for various empirical coefficient α.

D. Comparison with experimental data

Numerical results are compared with experimental measurement of Saville (from Shao et al. [4]) and numerical results produced by Kobayashi and Wurjanto [13], Hu et al. [5] and Shao et al. [4]. The last author uses an incompressible SPH method with an initial particle spacing $dx=dy$=0.10m.

The dimensionless average overtopping discharges, $Q/(H(gH)^{1/2})$, where g is the gravity, H the wave height and Q the overtopping discharge, is presented Figure 15. SPHysics results for various particle densities are included in the figure. Numerical model was run considering the SPS model and XSPH correction parameter ε_{XSPH}=0.0. Figure 16 shows the error of calculated overtopping discharges compared with experimental results.

Numerical results converge to experimental data of Saville as particle density increases. Error for particle density with particle spacing smaller than 0.05 is less than 5%. For these particle densities, mean overtopping discharge is well reproduced by the numerical model. The present results agree better with experimental measurement of Saville than the numerical result of Shao et al. [4], with an error around 25%, Kobayashi and Wurjanto [13] and Hu et al. [5], with an error around 60% and 40%, respectively.

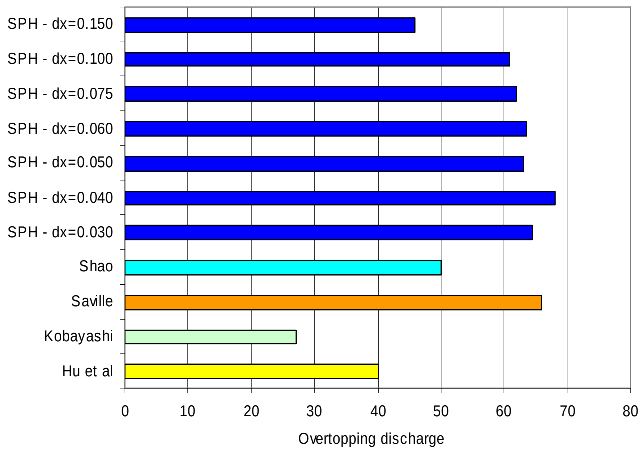

Figure 15. Mean overtopping discharge: comparison between numerical results and experimental data.

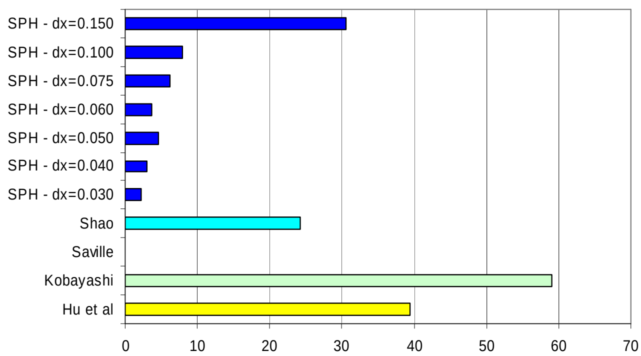

Figure 16. Overtopping discharge: error between numerical results and experimental data.

IV. Applications to Coastal Structures

Physical modelling performed in flume considering scaled model of coastal structures allows validating numerical model since field data for prototype structures are not easy to obtain. Here, the results of SPH numerical model are compared with experimental measurement obtained for a typical impermeable coastal structure with a slope of 2:3.

A. *Experimental setup*

The experimental tests [9] were performed in the framework of the Composite Modelling of the Interactions between Beaches and Structures (CoMIBBs) project - HYDRALAB III European project, to study the influence of the physical model scale in the simulation of wave propagation on coastal defences, in particular where the wave breaking phenomena plays an important role.

Several tests had been made in two different wave flumes. The case study used in this paper corresponds to the test performed in the large wave flume of LNEC with 3 m width, 73 m length and 2 m height (Figure 17). The flume is equipped with 6 wave gauges, 4 sensor pressures at the structure, and one overtopping device designed to measure the overtopping volumes of water.

A special attention was paid to the breaking area where video cameras were located, allowing the analysis of the wave breaking characteristics. The incident regular wave used here has a period, T=3.79 s, a wave height, H=0.40 m, and water depth is d=1.5 m. The wave length is in this case 12.04m. The bottom profile is composed by a horizontal bottom with 35.74m length and a bottom with a slope of 1:20 during 18.675m. The impermeable structure has a slope of 2:3 and the crest is located at 1.684m from the bottom, i.e. Rc=0.534m.

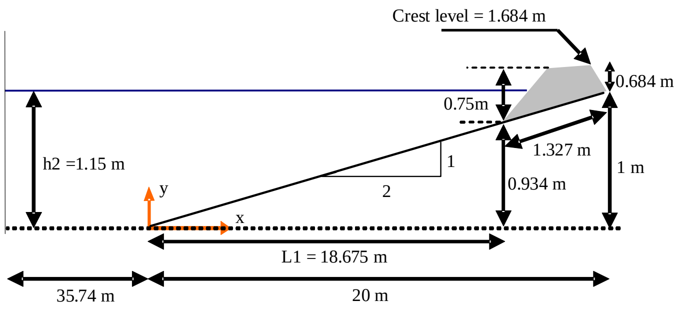

Figure 17. Wave channel and cross section of the case study.

B. *Numerical modelling*

The computational domain consists in 62000 fluid particles with initial particle spacing equal to 0.02m.

SPS turbulence model is used and it was adopted the XSPH parameter ε_{XSPH}=0. Quadratic kernel is also used for this case.

Wave generation is performed by a piston wavemaker without dynamic absorption. In the numerical simulations, the wave paddle is located at a distance of 10.0m from the beginning of the beach slope. Thus the horizontal bottom is smaller than that of the experimental configuration.

C. *Results and discussion*

Numerical simulation is performed for a total time of 70s, with a mean time step equal to 10^{-4}s. A flexible paddle is used for regular wave generation. The flexible paddle allows to impose an horizontal velocity profile similar to the wave profile in the correspondent section of the flume. Analysing the spectrum of the free surface elevation history at 10m before the beginning of the slope, it can be seen that harmonics have only a very small contributions. So, the regular wave obtained using the flexible paddle is similar to the experimental wave.

Figures 18 and 19 present the time-history of free surface elevation at two gauges located at 7.5m and 12.0m after the beginning of the beach slope, respectively. Comparisons between experimental measurements and numerical results show good agreement.

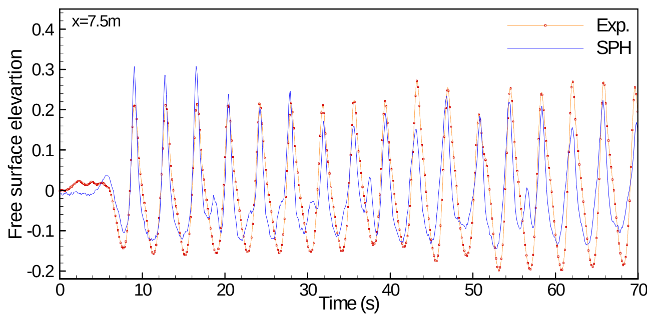

Figure 18. Free surface elevation at 7.5m from the beginning of the beach slope: comparison between experimental and numerical results.

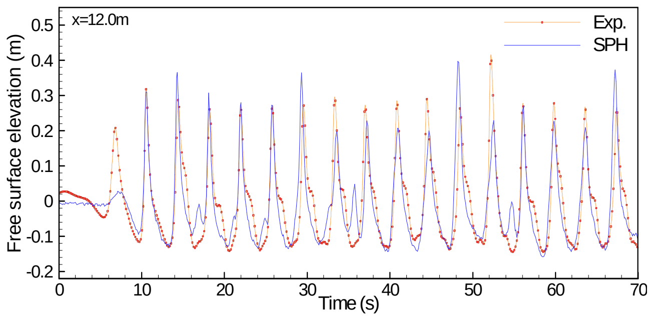

Figure 19. Free surface elevation at 12.0m from the beginning of the beach slope: comparison between experimental and numerical results.

Figure 20 shows the mean overtopping discharge and compared experimental data with numerical results. For numerical results, mean overtopping is calculated between the 2nd and 5th waves and the 2nd and 8th waves. As the paddle is not designed for dynamic wave absorption, re-reflexion occurs in the numerical flume and only some waves make it possible to calculate the mean overtopping discharge. The experimental tests were repeated for 6 times, allowing the definition of a confidence interval for the overtopping discharge.

As can be seen, numerical results and experimental measurements are in good agreement: numerical estimation of mean overtopping discharge is included in the interval of experimental measurements. The difference in the overtopping discharge obtained from the numerical model is due to the number of waves considered for the calculation.

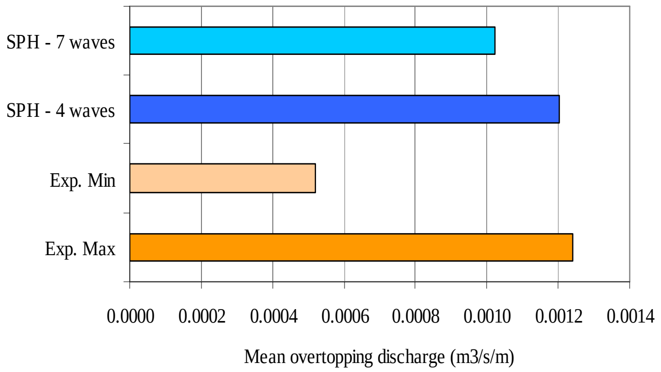

Figure 20. Mean overtopping discharge: comparison between numerical results and experimental measurement.

Figure 21 shows the snapshot of free surface near the sea wall structure. It can be seen the ability of SPH method to model very complex phenomena that occur in this type of fluid-structure interaction, such as the overtopping and run-up and wave-wave interaction, such as the interaction between the incident wave and the reflected wave by the sea wall structure.

V. CONCLUSIONS

Numerical model based on SPH presents a very interesting option to address coastal processes, particularly run-up, wave breaking and overtopping phenomenon that occurs in practical problems in coastal engineering. These problems involve complicated free surface deformations and, eventually, a complex structure for that SPH model is an ideal approach to simulate. For local studies of interaction between waves and structures, such as coastal structures, numerical modelling also presents a very attractive complement to physical modelling.

The weakly compressible numerical model SPHysics was used in the study of interaction between waves and a sea wall structure and, in particular, the overtopping discharge. A convergence study with the particle density values is carried out and the influence of ε_{XSPH} parameter and the viscosity model is defined. Result analysis show that instabilities occur when ε_{XSPH} value is different from zero and that seems to be better to use this value in future wave propagation simulations. It was also shown that convergence with particle density is not very clear. Overtopping is a very sensitive parameter and strongly depends on the wave breaking and other nonlinear processes that occur in front of the sea wall structure. Even thus, overtopping discharge results are not very different from the measured one if the discretization is sufficiently refined. Finally it was shown that wave height and overtopping are strongly dependent from the empirical parameter α of the artificial viscosity model. Consequently, it seems better to use the Sub-Particle Scale model.

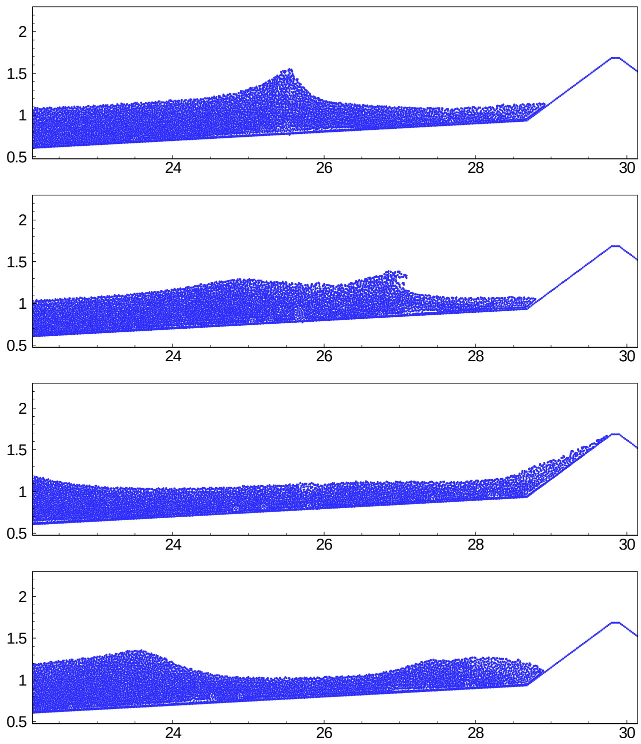

Figure 21. Snapshot of free surface near the sea wall structure.

Numerical model is used for modelling experimental scale model tests of wave propagation through a sea wall structure performed in a wave flume at LNEC. Results of wave height and overtopping obtained by the numerical model present good agreement with experimental measurements.

These results show that SPHysics model is a very promising tool to be used in future applications, as for example, to elaborate maps of risk in coastal areas, although the present model and computational resources only permit the used of simplified geometries and impermeable structures.

ACKNOWLEDGEMENT *(HEADING 5)*

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