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Wave overtopping of a typical coastal structure of the Portuguese coast using a SPH model

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ABSTRACT

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Smoothed Particle Hydrodynamics (SPH) method is a mesh-free, Lagrangian, particle method for modeling free-surface flows. The potential range of applications is very wide (waves, impact on dams, offshore...) as the mesh-free technique facilitates the simulation of highly distorted fluids/bodies, whereas Eulerian methods can be difficult to apply. Models based on SPH are an option to address coastal processes, particularly the interaction between waves and coastal structures, i.e. wave overtopping, that is a practical problem in coastal engineering. It involves complicated free surface deformations and SPH model is an ideal approach to simulate such a process. The paper presents an engineering application of SPH model to define the efficiency of a typical coastal structure of the Portuguese coast under stormy conditions. The model is used to characterize the run-up, free surface elevation near the structure and overtopping of the coastal structure, determining the maximum water velocity and water height over the structure. It is shown that numerical results, obtained for the prototype, present a similar trend comparing with data from physical modeling performed in test flume, using a model scale of 1:40.

ADITIONAL INDEX WORDS: *Interaction wave-coastal structure, Lagrangian model, hydrodynamics.*

INTRODUCTION

Seawalls 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 exerted 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 are complexes too: impermeable and porous structures, composed by blocs or arc crown wall structures, etc.

Project design of coastal structures is frequently based on empirical formula. However, their domain of applications is in general reduced, since formulas are valid for the narrow range of wave characteristics and geometries used in those developments.

Actually, in practical engineering projects, complex coastal structures are constructed using new geometries for which applicable empirical formula do not exist. For those cases, physical modeling is currently employed due to the accuracy of this approach and the possibility to model large areas. However, its accurate simulation on physical models strongly depends on the model scale used and needs an understanding of model and scale effects for the correct representation of the phenomenon.

For local studies of interaction between waves and structures as coastal structures, numerical modeling presents a very attractive complement to physical modeling. However, only some numerical models allow simulating wave breaking and wave overtopping correctly. 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 a Volume of Fluid (VOF) approach, such as the non-linear shallow water equations model AMAZON (REIS *et al.*, 2008) and the Reynolds Average Navier-Stokes (RANS) model COBRAS-UC (LARA *et al.*, 2006; NEVES *et al.*, 2008). However the recent advances on Smoothed Particles Hydrodynamics (SPH) models shows that Lagrangian method is very promising alternative approach to simulate wave breaking and overtopping due to its completely mesh-free technique.

The paper presents the basic principles of SPH method and the numerical model SPHysics (CRESPO *et al.*, 2008; CRESPO, 2008). SPHysics was used with success in previous studies by DIDIER and NEVES (2008), where numerical results of seawall overtopping agree well with experimental data. An engineering application of SPH model to define the efficiency of a typical coastal structure of the Portuguese coast under stormy conditions is described. The numerical model allows characterizing the run-up, the free surface elevation near the structure, the wave overtopping discharge, the maximum water velocity and the water height over the structure. It is shown that numerical results of wave overtopping discharge, obtained for the real seawall structure, present a similar trend comparing with data from a physical model performed in a test flume, using a model scale of 1:40.

EQUATIONS

SPH method was first developed and applied for astrophysics (LUCY, 1977; GINGOLD and MONAGHAN, 1977) and later for hydrodynamics simulations (MONAGHAN, 1994) and coastal applications (DALRYMPLE *et al.*, 2001). SPH approach is completely different from the Eulerian approach, i.e. grid models.

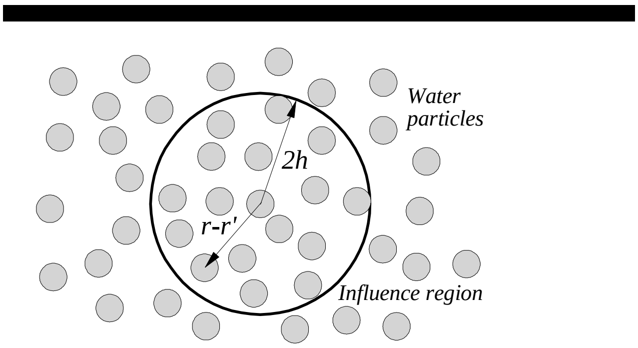

Figure 1. Typical compact support of the kernel function

The SPH is a free-mesh, purely Lagrangian, particle method for modeling fluid flows that facilitates the simulation of problems that require the ability to treat large deformations, complex geometries, nonlinear phenomenon and discontinuity. The method requires only particles where the fluid (water in this case) is present, so computational time is not wasted for computing empty areas. Moving boundaries, such as a piston wavemaker or bodies, are easily implemented.

Mesh-free particle methods treat the system as a set of particles which represents small volume of water, for hydrodynamics applications. So, for Computational Fluid Dynamics (CFD), variables such as mass, position, velocity, density, etc. which are transported by the particles are computed for each particles.

Smooth particle hydrodynamics approach

SPH method consists to integrate the hydrodynamics equations of motion on each particle in the Lagrangian formalism. The partial differential equations of continuum fluid dynamics are transformed into SPH forms, i.e. particle forms, by integral equations using integral interpolants (GINGOLD and MONAGHAN, 1977; MONAGHAN, 1992; LIU and LIU, 2003). The fundamental principle is to approximate any function *A(r)* by:

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

where *r* is the vector position, *W* is the weighting function, *h* is called the smoothing length. The interpolation function, i.e. weighting functions or kernels, allows determining the interaction among neighboring particles, included in the influence domain controlled by the smoothing length *h*, typically higher than the initial particle separation. Figure 1 shows a typical compact support of a kernel function. The kernels should be verified several conditions of positivity, compact support, Delta function behavior. Different kernels were developed and can be found in the literature (LIU and LIU, 2003). The relation given in Eq.1 is written as an approximation of the function *A* at a particle *a*, in discrete notation:

$$A(r) = \sum_b m_b \frac{A_b}{\rho_b} W_{ab} \qquad (2)$$

where the summation is over all the particles within the region of compact support of the kernel function. The mass and density are noted m_b and ρ_b respectively and $W_{ab}=W(r_a-r_b,h)$ is the kernel.

Two types of SPH model were developed: strict incompressible and weakly incompressible SPH model. The major differences between the weakly compressible SPH (LUCY, 1977; MONAGHAN, 1992; DALRYMPLE *et al.*, 2001) and the incompressible SPH (SHAO and LO, 2006; GOTOH *et al.*, 2004) lie in that the former calculated the pressures explicitly using an equation of state, while the latter employs a strict incompressible formulation for what the pressure is obtained implicitly by solving a pressure Poisson equation derived from the mass and momentum equations.

SPHysics model

SPHysics model is an open-source SPH solver inspired by the formulation of Monaghan (MONAGHAN, 1992) and developed jointly by a group of researchers of various universities (CRESPO *et al.*, 2008). 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 re-initialization: Shepard or MLS;
- Solid boundary conditions: Dynamic boundaries, repulsive forces, periodic open boundaries.

Detail of numerical implementation and references are available in CRESPO *et al.* (2008) and CRESPO (2008).

For the present bi-dimensional numerical simulations, the quadratic kernel (LIU and LIU, 2003) 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 provided by BATCHELOR (1974). 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. So, the mean time step is $2.1.10^{-4}$s.

A Sub-Particle Scale (SPS) approach to modeling turbulence, first described by GOTOH *et al.* (2001, 2004) and adapted later for weakly incompressible fluid by DALRYMPLE and ROGERS (2006), is used. Governing equations are spatially averaged over a length scale comparable to the particle size. The averaged equations allow solving directly the large-scale eddies, larger than particle size. For the smaller turbulent eddies, smaller than the particle size, a closure scheme is needed to model their effects on the flow. The SPS turbulence model is based on the Large Eddy Simulation (LES) concept, and so that kinetic eddy viscosity is defined using the Smagorinsky constant, *Cs*=0.12, the initial particle spacing and the local strain rate.

Integration in time is performed by the Predictor-Corrector model using a variable time step.

The repulsive boundary condition, developed by MONAGHAN, (1999), allows to prevent a water particle crossing a solid boundary.

Particles are usually moved using the XSPH velocity correction of MONAGHAN (1989). The method consists in recalculate the velocity of a particle taking into account the velocity of that particle and the average velocity of neighboring particles, using a constant ε, whose values ranges between zero and unity; $\varepsilon = 0.5$ is often used. This correction lets particles to be more organized. However, instabilities appear more or less rapidly when modeling wave propagation using $\varepsilon = 0.5$, i.e. particles gather, minimum distance between particles is not respected, velocity of that particles increases until particles penetrate solid boundaries. A numerical study shows that the value of ε would be smaller than the usually value: $\varepsilon << 0.5$. In the present simulations ε is taken to

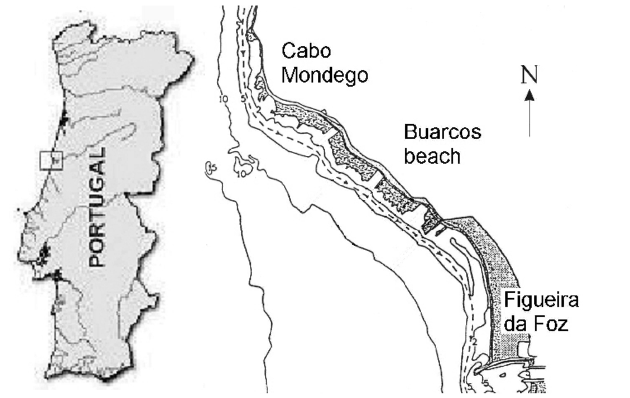

Figure 2. Location of the study area (FREIRE *et al.*, 2004)

0, i.e., that velocity correction is not performed, and a good stability is obtained.

Wave generation is performed using a piston wavemaker without dynamic absorption. In the numerical simulations, the wave paddle is located on a horizontal bottom before the beginning of the beach slope.

Fluid particles were initially placed on a uniform grid with dx=dz=0.2m and zero initial velocity. An initial density and pressure are assigned to the particles depending on the water height column. Solid particles are fixed and placed respecting the uniform grid used for placing fluid particles. The total number of particles is 67310, with 1953 solid particles for all computations.

The present wave paddle is not designed to absorb the reflected waves from the downstream side thus the numerical model can not be run for a long time. Simulations are performed for 140s. The CPU cost is around 120 hours using a PC Pentium Dual Core 3.4GHz and 2.0Go RAM.

CASE STUDY

The seawall of Buarcos is used to study the ability of the SPHysics model to determine the efficiency of a coastal structure, in what concerns to wave overtopping. This seawall is one example of a coastal structure built to protect the coast and to provide the necessary security for the coastal road that follows the shoreline.

The site of Buarcos is located in the central Atlantic west coast of Portugal, north of the city Figueira da Foz (Figure 2). Buarcos beach is a narrow sandy beach, 1.5km long, limited landward by urban infrastructures, namely a coastline protection adjacent to a seaside avenue. The seawall was re-constructed in 1998, after a winter storm: the existing protection suffered severe damage during this event.

In the absence of local wave records, FREIRE *et al.* (2004) made a characterization of the wave climate in the nearshore region of Buarcos based on the observation in a directional wave buoy located in front of Leixões, about 120km north of Buarcos. The methodology TRANSFER (COLI *et al.*, 2002) was used to obtain the nearshore wave regimes in front of the Buarcos beach, at different points placed at the -10.0m Chart datum (CD).

The efficiency of the seawall is analyzed considering the characteristics of the quite severe storm that occurred during almost one month of observations between January 19 and February 6 of the year 2001. In that period, the most extreme event corresponds to a maximum significant wave height, *HS* that reaches values between 7.2 and 7.4m for a mean wave period, *TZ*, of 12s.

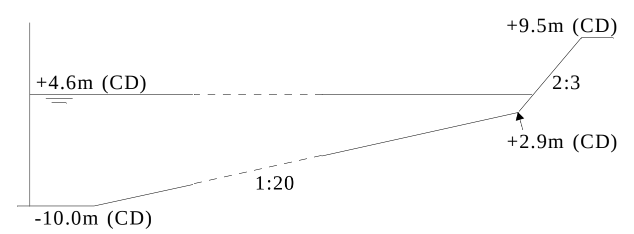

Figure 3. Schematic topography profile

The Lagrangian model is applied to a geometry that mimics the topography of the coast and the seawall (Figure 3). The bottom profile is composed by 15m length horizontal platform, which corresponds to the distance between the wave paddle and the beginning of the beach slope, and a 286.6m length beach represented by a 1:20 slope. The impermeable structure has a slope of 2:3 and the crest is located at +9.5m (CD).

The wave testing conditions chosen for the Buarcos site represents a typical 'storm' sea-state for this part of the coast. This very strong storm condition allows to investigate the behavior of the structure under heavy wave attack.

The higher water level +4.0m (CD) corresponds to the maximum tide at the Buarcos side, which may appear once or twice a year. An additional increase of the water level of 0.6m caused by other factors but the tide like wind, waves and the storm itself, is considered. For instance, a storm usually comes along with low pressure and this slightly increases the sea level. It is very unlikely that the water level actually rises up to a value of +4.6m (CD), and therefore this can be considered as the most extremely condition. With these considerations, the water depth at the seaward boundary is 14.6m (i.e., the wave regime was defined at -10.0m (CD)), the water depth at the toe of the seawall is 1.7m and the crest level of seawall above the still water is 4.9m.

Two mean wave periods are considered, 12s and 15s. Corresponding wave length at the seaward boundary is 133m and 171m, respectively. The mean significant wave height, *HS*, observed during the storm is 5.0m, with a minimum of 4.0m and a maximum of 7.2m (FREIRE *et al.*, 2004). For the numerical simulations, monochromatic wave height, *H*, varies from 2.0m to 8.0m.

RESULTS AND DISCUSSION

Results of maximum run-up, *R*, overtopping discharge per wave, *Q*, maximum water velocity, *V*, and maximum water height over the seawall, *Hw*, are presented and analyzed. The run-up is defined as the maximum water level above the still water surface. To calculate the overtopping discharge per wave, a particle counter is located at the beginning of the seawall crest. Results of the maximum run-up above the still water and the maximum water height over the seawall (overtopping cases) are written as the water level, *Hw*, in reference to the seawall crest: run-up take negative value and overtopping water height take positive value.

Tables 1 and 2 show the simulation results obtained for wave period T=12s and T=15s respectively. Maximum run-up, *R*, maximum water level, *Hw*, maximum water velocity over the seawall, *V*, and overtopping discharge per wave, *Q*, are presented. Moreover, the symbol ">" before the run-up value indicates that overtopping occurs.

Figure 4 summarizes the maximum water level, *Hw*, above the seawall crest obtained for the two wave periods. The position of the seawall crest is indicated in the figure. The maximum water level increases when wave height increases.

Table 1: Maximum run-up, maximum water height, maximum velocity and overtopping for wave period *T*=12s.

H (m)	*R* (m)	*Hw* (m)	*V* (m/s)	*Q* (m^3/wave)
2.0	4.18	-0.77	0.0	0.0
3.0	4.46	-0.49	0.0	0.0
4.0	4.80	-0.15	0.0	0.0
4.5	4.75	-0.20	0.0	0.0
5.0	4.80	-0.15	0.0	0.0
5.5	4.85	-0.10	0.0	0.0
6.0	4.90	-0.05	0.0	0.0
7.2	>4.95	+0.32	1.11	0.16
8.0	>4.95	+0.35	3.80	0.52

Table 2: Maximum run-up, maximum water height, maximum velocity and overtopping for wave period *T*=15s.

H (m)	*R* (m)	*Hw* (m)	*V* (m/s)	*Q* (m^3/wave)
2.0	4.43	-0.52	0.0	0.0
4.0	4.54	-0.41	0.0	0.0
6.0	>4.95	+0.19	0.74	0.04
8.0	>4.95	+0.64	6.20	3.60

As can be observed for *T*=12s, overtopping does not occur for wave height $H \leq 6.0$m. However, the water almost reached the seawall crest for wave height between 4.0m and 6.0m. Overtopping occurs for the higher waves (*H*=7.2m and 8.0m). For *T*=15s, overtopping does not occur for wave height $H \leq 4.0$m and occurs for the higher waves (*H*=6 and 8 m). For both periods, overtopping discharge increases with the wave height, like the maximum velocity over the seawall and the water height over the crest of the structure.

As can be seen, for *T*=12s and *H*=7.2m and for *T*=15s and *H*=6.0m the overtopping volume is just 0.16m^3 and 0.04m^3 respectively. Since the particle volume is 0.04m^3 (due to the initial discretization *dx*=*dz*=0.2m), overtopping corresponds to only 1 and 4 particles for these two cases, which is not significant.

For *T*=12s and *H*=8.0m, when overtopping occurs, the water velocity attained 3.8m/s, the water discharge is 0.52m^3 and the water height over the structure is 0.52m. For *T*=15s and *H*=8.0m, the water velocity attained 6.2m/s, the water discharge is 3.6m^3 and the water height over the structure is 0.64m. For both extreme waves, green water occurs, i.e. water overtops the structure.

In order to analyze the goodness of the results obtained with SPHysics numerical model, a comparison is made in Table 3 with results of physical model tests performed in a bi-dimensional tank at the LNEC, using a 1:40 prototype model scale for *T* =12s (SILVA and LEMOS, 2000). It should be pointed out that, for *T*=12s, test in the physical model was performed until *H*=5.0m.

In the physical model, overtopping was reported in a qualitative way using numeration from 0 to 5, as follows: 0 - none, no overtopping; 1 - slight, beginning of overtopping, i.e. for the maximum wave heights spray overtops the structure; 2 - small, frequent passage of spray over the structure; 3 - moderate, for maximum wave heights there is green water overtopping the structure; 4 - important and 5 - serious. Levels 3 to 5 are not observed in physical tests. In order to compare the results of the physical and numerical model, the maximum water level, *Hw*, obtained in the numerical model is compared with the overtopping classification obtained in the physical model. As can be seen, numerical results of *Hw* and qualitative physical classification are in good accordance. When run-up closely reaches the crest of the seawall, overtopping classification is 2. It seems realistic since with water just 0.15m to 0.50m below the crest of the seawall, spray of water occurs. For the lower wave height, the value of 1 seems also in accordance with the numerical results.

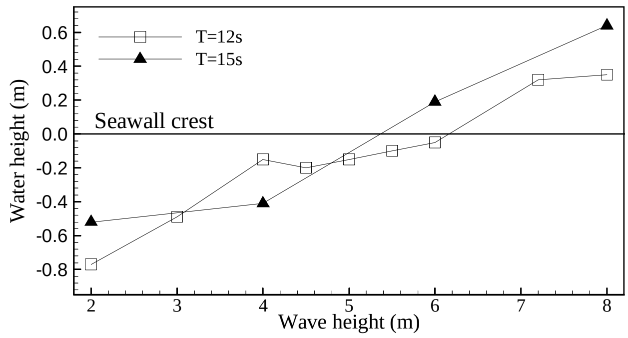

Figure 4. Maximum water height *Hw* versus wave height *H*, for wave period *T*=12s and *T*=15s. Run-up corresponds to negative water height values and overtopping to positive values.

Table 3: Comparison of overtopping classification results between the numerical simulations and the physical model tests for wave period *T*=12s.

H (m)	*Hw* (m)	Overtopping classification
2.0	-0.77	1
3.0	-0.49	2
4.0	-0.15	2
4.5	-0.20	2
5.0	-0.15	2

As an example, Figure 5 shows the position of the particles for *H*=3.0m and *T*=12s: run-down caused by the previous wave induces a reflected wave; a strong interaction between breaking incident wave and reflected wave occur and produce a large "splash"; the incident wave collision with the base of the seawall induce the associated run-up. For higher wave height, overtopping is observed over the seawall crest.

CONCLUSIONS

Model based on SPH are an option to address coastal processes, particularly run-up, wave breaking and overtopping, phenomenon that appears in practical problems in coastal engineering. These problems involve complicated free surface deformations and, eventually, complex structures and so that SPH model is an ideal approach to simulate them.

The SPHysics model is used for a real engineering case that consists in analyze the efficiency of a typical coastal structure of the Portuguese coast, the Buarcos seawall, under stormy conditions. Results of overtopping obtained by the model presents similar trend comparing with qualitative data obtained from a physical model performed in a bi-dimensional test flume using a model scale of 1:40.

These results show that SPHysics model is very promising as a tool to be used in future application 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.

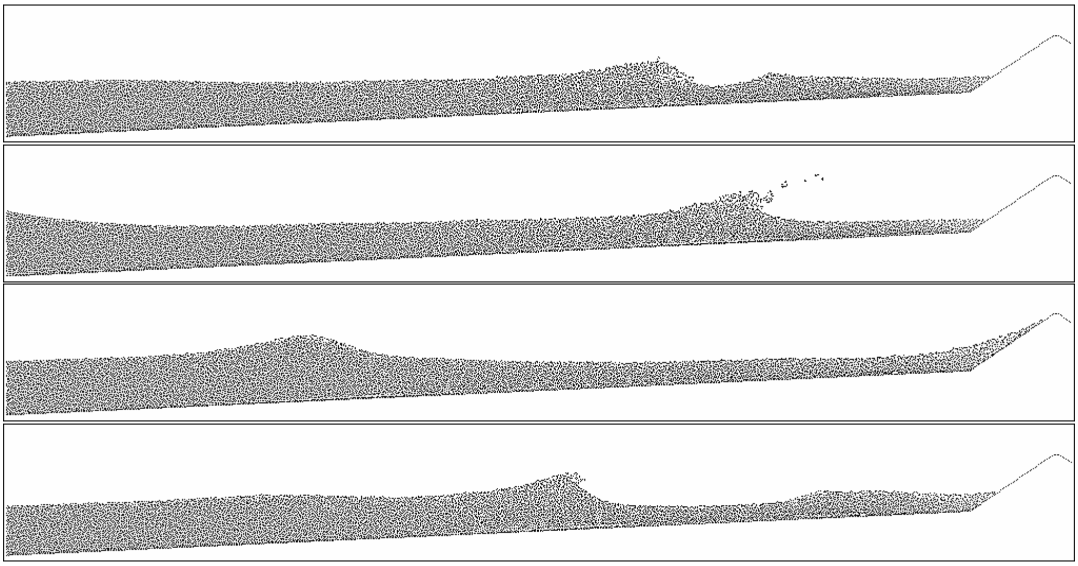

Figure 5. Position of particles for H=3.0m and T=12s at different times

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