Abstract: - The final design of coastal defenses requires a proper evaluation of actions exerted by the sea waves. Usually wave run-up and wave overtopping are used to define the geometry of coastal defenses and the choice of materials that form such structures. However, the wave loadings (forces and/or pressures) have to be estimated to finalize the design and to verify the global structural stability and the possible occurrences of local damages. Depending on design (e.g. foundation systems, materials, armours), each coastal defense can be schematized as a monolithic structure or a space frame. The loading assessment will depend on such schematization. For the most classical coastal defenses (caissons, breakwaters, sea dikes) plenty of literature exists for the wave loading assessment. However, when the geometrical layout or the hydrodynamic conditions differ from the most used ones, there is no formula or method that can easily help for the purpose. In such a case, only physical or numerical modelling can provide the requested results. This is for example the case of the Belgian harbors of Zeebrugge and Blankenberge, for which an upgrade of the existing coastal defenses has been foreseen. The wave loading assessment for these new structures has been carried out at Flanders Hydraulics Research, in Antwerp (Belgium). The SPH-based and mesh-free DualSPHysics numerical model has been used for the numerical force assessment. By means of the numerical modelling, it was possible to investigate further aspects strictly related with the structural design, such as the influence of the wave period on the maximum wave forces and the effects of a parapet built in addition to a vertical storm return wall. The present work gives an overview of the force assessment achieved using DualSPHysics and discusses the aforementioned investigation aspects. The use of numerical modelling for the design of coastal structure is proven as a reliable alternative to experimental campaigns, usually expensive and time-demanding.

Key-Words: - Smoothed Particle Hydrodynamics, wave forces, numerical modelling, coastal structures, DualSPHysics, structural design

1 Introduction
The increasing storminess of the last decades, as dramatically remarked by the most recent events in the Northern Sea (e.g. Xaver storm in December 2013), is compelling many Countries in Europe to review their coastal hazards concepts in order to upgrade the existing coastal defenses with the general intent of guaranteeing reasonable standards for human safety in extreme storm conditions. The Belgian coastline is one of the zones most exposed to wave attack and flooding, since it is a low lying and very densely populated area with high touristic and recreational value. The Flemish Coastal Safety Masterplan was approved ([1]) to tackle these problems through the construction of new coastal defenses or the renovation of the existing ones. To do so, the actions exerted by sea waves on the coastal structures have to be properly characterized. The final aim is to reduce local damages and to prevent the onset of failure mechanisms that might have disastrous consequences for the coastal local communities. Unfortunately, the existing approaches (i.e. semi-empirical formulae) do not
cover all possible cases, especially when the particular geometry or hydraulics conditions differ from those used to calibrate such approaches.

A possible solution consists in conducting physical model experiments, however experimental campaigns often require high costs and resources.

For all these reasons, numerical modelling represents an alternative technique and cheap solution as useful tool to analyze the interaction between sea waves and coastal structures.

The present work describes the application of a meshless numerical model for the analysis of wave forces on coastal structures to face real-life problems from the Belgian coast. The DualSPHysics model (www.dual.sphysics.org), based on the Smoothed Particle Hydrodynamics method, has been used for the purpose. The cases of study consist of new storm walls or coastal defenses proposed for the main harbor of Zeebrugge and for the Blankenberge marina in Belgium.

The accuracy of DualSPHysics for wave loading modelling has been already proved, as shown in [3]. In this work, the results are extended to analyze the influence of different geometries and hydraulic conditions on the calculated wave forces.

2 DualSPHysics model

DualSPHysics is a numerical model based on the Smoothed Particle Hydrodynamics (SPH) method ([8]). SPH is a Lagrangian and meshless method where the fluid is discretized into a set of particles and each of these particles are nodal points where physical quantities (e.g. position, velocity, density, pressure) are computed as an interpolation of the values of the neighboring particles. The contribution of the nearest particles is weighted according to distance between particles and a kernel function, $W$, is used to measure this contribution depending on the interaction distance that is defining using a smoothing length, $h$.

The mathematical fundamental of SPH is based on integral interpolants, therefore any function $F$ can be computed by the integral approximation. This function $F$ can be expressed in a discrete form based on the particles. The approximation of the function is interpolated at particle $a$ and the summation is performed over all the particles within the region of compact support of the kernel:

$$F(r) = \int F(r')W(r-r',h)dr'$$  \hspace{1cm} (1)

$$F(r_a) = \sum b F(r_b)W(r_a-r_b,h) \frac{m_b}{\rho_b}$$  \hspace{1cm} (2)

where the volume associated to the neighboring particle $b$ is $m_b/\rho_b$ with $m$ and $\rho$ being the mass and the density, respectively.

The kernel functions $W$ must fulfill several properties ([15]), such as positivity inside the area of interaction, compact support, normalization and monotonically decreasing with distance. One option is a quintic kernel where the weighting function vanishes for inter-particle distances greater than $2h$.

In the classical SPH formulation, the Navier-Stokes equations are solved and the fluid is treated as weakly compressible ([11]). The conservation laws of continuum fluid dynamics, in the form of differential equations, are transformed into their particle forms by the use of the kernel functions.

The momentum equation proposed by [15] has been used to determine the acceleration of a particle $(a)$ as the result of the particle interaction with its neighbors (particles $b$):

$$\frac{dv_a}{dt} = -\sum b m_b \left( \frac{P_b}{\rho_b^2} + \frac{P_a}{\rho_a^2} + \Pi_{ab} \right) \nabla a W_{ab} + \mathbf{g}$$  \hspace{1cm} (3)

being $v$ velocity, $P$ pressure, $\rho$ density, $m$ mass, $g=(0,0,-9.81)$ ms$^{-2}$ the gravitational acceleration and $W_{ab}$ the kernel function that depends on the distance between particle $a$ and $b$. $\Pi_{ab}$ is the viscous term according to the artificial viscosity proposed in Monaghan (1992). The mass of each particle is constant, so that changes in fluid density are computed by solving the conservation of mass or continuity equation in SPH form:

$$\frac{dp}{dt} = \sum b \mathbf{v}_{ab} \cdot \nabla_b W$$  \hspace{1cm} (4)

In the weakly compressible approach, the fluid is treated as weakly compressible and Tait’s equation of state is used to determine fluid pressure based on particle density. The compressibility is adjusted so that the speed of sound can be artificially lowered; this means that the size of time step taken at any one moment (which is determined according to a Courant condition, based on the currently calculated speed of sound for all particles) can be maintained at a reasonable value. Such adjustment however, restricts the sound speed to be at least ten times faster than the maximum fluid velocity, keeping density variations to within less than 1%, and therefore not introducing major deviations from an incompressible approach. Following [6], the relationship between pressure and density follows the expression:

$$P = B \left[ \left( \frac{\rho}{\rho_0} \right)^7 - 1 \right]$$  \hspace{1cm} (5)
\[ B = \frac{c_o^2 \rho_0}{\gamma} \]  

(6)

where \( \gamma = 7 \) and \( \rho_0 \) is the reference density. The speed of sound \( c_o \) defined at the reference density and it is numerically computed like at least 10 times the maximum velocity in the system that is determined as the wave-front velocity of a dam-break.

\[ c_o = \text{coef}_{\text{sound}} \sqrt{g \cdot h_{\text{swl}}} \]  

(7)

being \( h_{\text{swl}} \) the still water level and \( \text{coef}_{\text{sound}} \approx 10^{-20} \). If the value of \( \text{coef}_{\text{sound}} \) is increased, then the compressibility of the fluid is decreased according to Equations (5) and (6).

The Symplectic time integration algorithm ([14]) has been used in the present work and a variable time step was calculated, involving the CFL (Courant-Friedrich-Lewy) condition, the force terms and the viscous diffusion term.

DualSPHysics has been developed by Universidade de Vigo (Spain) mainly in collaboration with the University of Manchester (U.K.). Nowadays an extensive network of DualSPHysics collaborators exists within Europe that encourages the development of the code towards practical applications (Fig.1).

### 3 Cases of study and numerical results

Two different cases of study are described and discussed in the following sections. Both cases are real applications of DualSPHysics model to coastal engineering problems.

#### 3.1 Zeebrugge dock area

The dock area of the harbor of Zeebrugge is one of the weak links in the Belgian coastal line. Countermeasures are foreseen to build new elements on the top of the existing quay walls in this area in order to reduce the overtopping discharge below tolerable limits. Fig. 2 shows the location of the area of interest (red line).

The geometry of the new structures has been defined to guarantee that the overtopping discharge will result under tolerable limit. However, the final design of each new structural element requires the evaluation of the wave forces acting on it.

An example of possible cross section from the dock area of Zeebrugge is shown in Fig. 3, where the existing structure (with a 1:2 slope) is heightened more than 1m above the quay level.

![Figure 1. DualSPHysics collaboration map.](image1)

![Figure 2. Location of the new sea walls in the port of Zeebrugge](image2)
Fig. 4 shows an example of the architectural design for a new trapezoidal element to be built on top of an existing quay wall in the same area: the height and position if this element are based on overtopping calculations. The new elements are designed to behave as a monolithic block against the wave action. Therefore the wave forces acting on them have to be evaluated for overall stability calculation.

The DualSPHysics model is used to evaluate the forces on such kind of new coastal defenses. The main advantages of using DualSPHysics to assess the wave forces can be summarized as follows:

- Thanks to its pre-processing routine, DualSPHysics is capable to model any kind of geometry in a very straightforward and computationally cheap way.
- DualSPHysics is based on the Graphics Processing Unit (GPU) technology that allows reducing significantly the runtime only using a graphic card instead of a normal CPU as execution device.
- Thanks to its meshfree nature, there is no need for special treatment of the surface, making the technique ideal for studying violent free-surface motion, e.g. wave breaking and impact.

The only approach found in literature to evaluate wave forces for similar configurations is represented by semi-empirical formulas proposed by den Heijer ([9]). However, den Heijer studied only storm return walls with vertical faces and not slopes or trapezoidal elements: sloping structures are generally less reflective and lead to higher overtopping rates than the vertical walls, so that less forces should be expected because a bigger part of the wave energy is transmitted behind the structure. Furthermore den Heijer’s formula can be applied for \( h_c/H > 1.3 \), where \( h_c \) is the crest level and \( H \) is the wave height. This condition does not correspond to the conditions of the present case of study. Thus the formulae proposed by [9] could not be used and the numerical modelling was preferred as viable alternative.

### 3.1.1 Wave forces and overflow velocities

The DualSPHysics model has been applied to assess the force exerted by sea waves on the new defenses for the entire dock area of Zeebrugge. All the results are reported in [2]. Here an example of wave forces and flow velocity assessment is reported for the cross section as depicted in Fig. 3.

The wave forces have been calculated both on the entire sea dike and on the upper part of it (i.e. above the quay level). The hydraulic boundary conditions have been extracted from [12].

Regular waves have been modeled with wave height \( H \) equal to 1.08m and mean wave period \( T \) equal to 2.8s. The water depth at the toe of the dike is 4.91m. The numerical resolution, expressed in terms of initial particle interspace, is equal to 0.05m. A snapshot of the numerical modelling can be seen in Fig. 5. The red box indicates the control volume where the average flow velocity is calculated.

The value of maximum horizontal force measured on the entire structure in the numerical model was 153.70 kN/m where the hydrostatic component in case of SWL (still water level) was about 90 kN/m. The force measured only on the crest of the structure, whose height is 1.36m above the quay level, resulted equal to 4.82 kN/m. Finally the maximum overtopping flow velocity, calculated as the peak flow velocity at the backward toe of the
structure, was measured. The magnitude of this velocity results about 8 m/s.

3.2 Blankenberge marina
The previous section has shown an application example of DualSPHysics for the design of coastal structures. The applicability of DualSPHysics to the wave impact forces on storm return walls for typical cases of Belgian harbors has been also demonstrated by [3]. The authors compare the numerical results with physical data from experimental campaigns conducted at Ghent University. Further comparisons, with Flow3D model, have been presented by [16]. The present section is meant to show the capabilities of the model to perform further analysis on the possible behavior of these coastal defenses. Two examples from Blankenberge marina are reported.

Blankenberge marina is another weak link along the Belgian coast. The countermeasures to prevent severe overtopping events consist of the construction of storm return walls on top of the existing quay walls all around the marina. An extensive study on wave overtopping and loading on these new structures has been carried out at Flanders Hydraulics Research. All the details can be found in [4].

Two different topics are analyzed and reported here: a) the influence of the wave period on the calculated wave forces on a storm wall; b) the differences in pressure distributions between a fully vertical wall and a parapet wall.

3.2.1 Wave period influence
The influence of the wave period on the results wave loading on the storm return wall has been analyzed. A sketch of the cross section is depicted in Fig. 6. The geometry consists of a vertical way with storm return wall on top.

When the wall is on the edge on the quay wall, no significant influence is expected and the forces and pressure are proportional to the incident wave height ([10]). When there is a berm before the storm return wall, as in Fig. 6, the wave period may influence the wave forces since the wave can break on the quay with the breaking depending on the relative wave length compared with the berm length and water depth.

Table 1. Influence of wave period on wave forces for a storm return wall located not at the edge of the quay.

<table>
<thead>
<tr>
<th>T_{SPH} [s]</th>
<th>H_{SPH} [m]</th>
<th>F/\rho g H^2 [-]</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.00</td>
<td>0.90</td>
<td>5.64</td>
</tr>
<tr>
<td>4.07</td>
<td>0.95</td>
<td>2.65</td>
</tr>
<tr>
<td>3.75</td>
<td>0.85</td>
<td>2.47</td>
</tr>
<tr>
<td>3.36</td>
<td>0.79</td>
<td>1.48</td>
</tr>
<tr>
<td>3.00</td>
<td>0.75</td>
<td>0.96</td>
</tr>
</tbody>
</table>

The analysis shows a clear influence of the wave period on the wave force. It can be observed that higher periods lead to higher forces.
3.2.2 Influence of parapet walls

Finally, an example is reported about the comparison of wave pressures exerted on a storm wall between a vertical and a parapet wall solution. Parapet walls are in general preferred to vertical walls because the presence of the parapet, on the seaward face of the structure, leads to less overtopping rates than with vertical walls. However, the inversion of the momentum of the overtopping flows hitting the parapet causes higher forces than on vertical wall solution. In general, the force exerted by sea waves on a vertical wall is 1.5-2 times smaller than the force exerted on a parapet wall with the same crest elevation ([13]).

In terms of pressure distribution, for a parapet wall a maximum in wave pressure is expected around the free-surface level, meanwhile for vertical wall a quasi-hydrostatic distribution is foreseen.

DualSPHysics model has been applied to a simple case with a sloping dike with storm walls to prove the capability of the model to catch the aforementioned differences. An initial particle interspace of 0.05m has been used. A snapshot of the modelling is shown in Fig. 8. The wave conditions at the numerical wave paddle are similar to those used for the case described in § 3.1.1. The sloping dike is the same as well, as the crest elevation determined by the height of the storm wall. The only difference is the presence of a seaward parapet in one of the case (top image in Fig. 8).

It is immediately noticeable that the wave pressure distribution is quasi-hydrostatic in the case of vertical wall. The overtopping flow, deviated by the wall is coming back seawards, reflected by the wall. The reflection process is the responsible of the wave pressures exerted on the wall as indicated in Fig. 8 (bottom panel). In the case of parapet wall (top panel), the waves are reflected seawards by the presence of the parapet. Physically this triggers high pressures where the wave momentum is inverted (around the free surface). Again, DualSPHysics seems to catch this behavior in a proper way.

4 Conclusions

The use and capabilities of DualSPHysics model is presented in the present work as support to the design of coastal structures. Cases of study have been selected from previous works carried out for the Belgian coast. Extensive validation work has been already reported in [16] and [3]. No further validation is presented in this work, where the focus is on the usefulness of DualSPHysics for practical purposes.

From one side, an example of application of DualSPHysics to calculate wave forces and overtopping flow velocities is shown. The advantage of using the numerical modelling is due to the fact that it is possible to represent any kind of geometry and any desired hydraulic condition. This make DualSPHysics a possible alternative predictive tool, whereas the existing approaches (such as semi-empirical formulas) are not applicable.

From the other side, further analysis on the DualSPHysics capabilities, to help the design of coastal structures, are shown. The influence of the wave period on the wave forces on storm walls is
analyzed. The differences in pressure distributions for vertical and parapet wall are shown. In both cases, DualSPHysics has represented a fast, cheap and reliable tool to characterize the wave-structure interaction phenomena.

Concluding, this work represents a further proof of the DualSPHysics improvements and achieved developments in terms of predictive tool for coastal engineers and structural designers.

References: