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Title: On the accuracy of DualSPHysics to assess violent collisions with coastal structures

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Abstract: The accuracy of DualSPHysics and IHFOAM to reproduce the propagation of a regular wave train and its collision with a vertical sea wall with a hanging horizontal cantilever slab was compared by different metrics (skill index, normalized standard deviation, correlation coefficient and root-mean square error). These metrics were applied to elevation of the free-surface and to the horizontal force exerted on the wall. The numerical results of both models converge to experimental values when increasing the resolution, being the accuracy similar for both models at high spatial resolution, although IHFOAM has a slightly higher performance than DualSPHysics for low and medium resolutions. Overall, the analysis suggests that mesh-less models have attained the level of maturity required to provide results with an accuracy equivalent to mesh-based models.

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Dear David Le Touzé,
Managing Special Issue Guest Editor
Computers and Fluids

We have updated the manuscript following the suggestions of the reviewers. A marked-up copy of the changes is now available from the previous article file as a new manuscript **CAF-D-18-00276_R1.docx**

We have revised our manuscript in response to the reviewers' comments, as detailed in the point by point responses.

We hope that the points raised by you and the referees have been addressed. We wish to thank kindly the referees again for their reviews and hope to hear from you again on the status of the manuscript.

Yours sincerely,
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Reviewers' comments:

Reviewer #1: This is generally a good and promising work comparing two benchmark numerical models for the wave-structure interactions. However, hope the authors could address the following issues if they think these comments are suitable.

[1] In the Introduction, it is suggested the authors add some literatures on fluid-structure interactions in SPH, which is more general than the wave-structure interactions. One example might be "An ISPH simulation of coupled structure interaction with free surface flows, Journal of Fluids and Structures 2014, 48, 46-61".

We are very grateful for your suggestions, and here we agree to include more literature examples such as:

[16] Marrone S, Antuono M, Colagrossi A, Colicchio G, Le Touzé D, Graziani G. δ -SPH model for simulating violent impact flows. *Computer Methods in Applied Mechanics and Engineering* 2011; 200(13-16): 1526-1542.

[17] Liu X, Lin P, Shao S. An ISPH simulation of coupled structure interaction with free surface flows. *Journal of Fluids and Structures* 2014; 48: 46-61.

[18] Sun P, Ming F, Zhang A. Numerical simulation of interactions between free surface and rigid body using a robust SPH method. *Ocean Engineering* 2015; 98: 32-49.

[19] Cao XY, Ming FR, Zhang AM, Tao L. Multi-phase SPH modelling of air effect on the dynamic flooding of a damaged cabin. *Computer and Fluids* 2018; 163: 7-19.

According to the reviewer suggestion we have also replaced the expression "wave-structure interaction" for the most general expression "fluid-structure interaction" in Introduction.

[2] I am slightly concerned about the following statement in the paper "However, as far as we know, neither the convergence of SPH results to experimental measurements in terms of the spatial resolution nor the comparison between mesh-free and mesh-based models have been analysed in detail". Maybe I am not correct, but I suggest the authors may soften this sentence a little, since I feel similar works have been done somewhere else. Two early such works immediately in my mind are:

- As for the comparison between mesh-free and mesh-based models: *Hui Pu J, Shao S, Huang Y, Hussain K. Evaluations of swes and sph numerical modelling techniques for dam break flows. Engineering Applications of Computational Fluid Mechanics* 2013; 7(4): 544-563.

- As for the convergence of SPH results to experimental measurements in terms of the spatial resolution: *Shao S, Gotoh H. Turbulence particle models for tracking free surfaces. Journal of Hydraulic Research* 2005; 43(3): 276-289.

The authors are suggested to review more similar works and then propose their work is an improvement over these.

We have modified the text according to this suggestion and we wrote:

"As far as we know, only a few works have dealt with the convergence of SPH results to experimental measurements in terms of the spatial resolution [30] or the comparison between mesh-free and mesh-based models have been analysed in detail [31]."

[3] Tables 1-3 may be merged or re-arranged into one Table, since the current tables are not in efficient use.

We have made some changes to follow the suggestion of the reviewer. We decided to remove the tables since the information can be included as plain text in the manuscript. In fact, the information of Table 2 is no longer relevant and it is not needed in this work.

The Table 1 has been replaced with the following text in the manuscript:

“The three first wave gauges (WG1, WG2 and WG3) were located in the part where the slope of the bottom of the wave flume is equal to zero and far from the structure while the rest of wave gauges (WG8, WG4, WG5, WG6 and WG7) were located near the structure and in the part where the slope is equal to 1/20. The distances from the wavemaker to the different wave gauges were 11.32, 11.81, 12.50, 20.59, 20.86, 21.25, 21.50 and 21.85 m.”

The Table 3 has been replaced with the following text:

“The water depth was equal to 0.605 m near the piston, and 0.105 m near the structure. The wave height and wave period of the generated wave were 0.065 m and 2.2 s, respectively.”

[4] Is IHFOAM a two-phase model? Then how to compare with SPH which is a single phase for all the numerical studies, since the two models are not compared on an equal basis, unless the authors can convince the influence of air is not substantial in the present case studies.

Good point, we will try to clarify this issue.

On the one hand, the authors carried out some tests prior to the cantilever simulations described in the manuscript to check the importance of air trapped between the water and the structure. Simply, the structure was perforated and a orifice was made at the where the horizontal and vertical walls join. This orifice allows air the leave the inner part of the structure when water hits the structure. Both time series of horizontal force, with orifice (no air effect) and without orifice, are very similar (differences smaller than 5%), which proves that air effect is negligible. This description was not detailed in the text for the sake of clarity, however it can be included if required by the reviewer. On the other hand, and considering the results shown in this paper for the case under study, the SPH solutions (only one phase) gives reasonable results comparing with experimental data and with IHFOAM, which means that the influence of air is not substantial here (as seen in Figures 3-8 in the manuscript).

[5] Suggest the authors to kindly provide CPU time for the two models to enrich the existing accuracy analysis.

Thanks the reviewer for this suggestion. We have included more information in the text:

“Although DualSPHysics simulations can be executed both on CPUs and GPUs, the computational time needed to run the case with the CPU version is considerably higher (~20 times) than with the GPU version. We should note that DualSPHysics is mainly optimized to be run on GPUs and the CPU version is mainly kept for development purposes.”

[6] Suggest the authors to quantify the convergence speed in view of spatial resolution. That is to say, based on the variable particle/mesh resolutions, please consider plotting errors and then quantifying the convergence speed such as first or second order accuracy of the two numerical models.

A convergence analysis was successfully applied to the movement of a dambreak tip by other authors (Shao and Gotoh, 2005). However, such analysis is not advisable here due to several reasons, some of them of experimental nature and some due numerical constraints. Experimentally, the complexity of the case is high, in such a way that the experiment is not

fully repeatable. Thus, the force signal is the average of several consecutive collisions which implies a considerable wave to wave differences. Numerically, both models were run with variable time step. This configuration is mandatory since the time step becomes extremely low during the collisions, which would hinder the efficiency of the model if used during the whole calculation. In fact, it would lead to unaffordable run times. Driving the analysis under variable time step conditions the convergence would be affected by changes in spacing and in time.

[7] The authors might need to clarify what conclusions to reach for this work. It seems the IHFOAM has a better accuracy across all the spatial resolutions and I also guess it is faster. Even if it is slower, this may be due to the two-phase setting of IHFOAM. So the overall conclusion might be SPH is slightly worse or better?

We have added more information about this issue:

“In summary, for the case under study, a meshless method like DualSPHysics is slightly worse in terms of accuracy and comparable in terms of performance than a state-of-the-art mesh-based model like IHFOAM. This is a remarkable fact since a decade ago the emerging models based on SPH technique were considered to be merely toy models that could be only used for oversimplified geometries (e.i.: [13], [53] and 54).”

[8] The figures may be improved either in resolution or presentation. For example, Figure 4, 6 and 7, 8 uses word "time" for x-axis but symbol for y axis. For Fig. 7, what are the two extra vertical lines in the middle?

According to the reviewer, the figures were modified and improved. We have produced figures with higher quality. In order to use symbols in both axis, we have replaced the word "time" in x-axis with "t". We have also removed the two extra lines in Fig. 7. New versions of the figures are included in the new submission.

Reviewer #2: This manuscript presents a comparison study of DualSPHysics and IHFOAM in simulating violent wave impact on fixed structures. The framework of this manuscript is ok. The discussions need to be more concise and rigorous. More detailed comparisons other than just showing the wave elevation and forces would be helpful. This manuscript can be considered for publication after the general comment and following specific queries are addressed.

1. The resolution of the figures can be further improved. It is hard to distinguish different curves, particularly at the important locations, in some figures.

Thanks the reviewer. The same comment was raised by reviewer #1. We have produced higher quality figures so we hope the problem is solved now. In addition, Figure 4 has been modified for a better visualisation.

2. It is not very necessary to add Table 1. The numbers can just be put in the text.

We have followed the suggestion of the reviewer and now the Table 1 has been replaced with the following text in the manuscript:

"The three first wave gauges (WG1, WG2 and WG3) were located in the part where the slope of the bottom of the wave flume is equal to zero and far from the structure while the rest of wave gauges (WG8, WG4, WG5, WG6 and WG7) were located near the structure and in the part where the slope is equal to 1/20. The distances from the wavemaker to the different wave gauges were 11.32, 11.81, 12.50, 20.59, 20.86, 21.25, 21.50 and 21.85 m."

3. In the paragraph after Figure 2, it says "The experimental sampling frequency in experiments was resampled according to the numerical one". This approach may miss the local extreme values in the experimental curve, which leads to an unfair comparisons.

Good point. Please let us explain this better and we hope you agree with our reasons.

The resampling was necessary exactly to avoid an unfair comparison. A very high experimental sampling frequency was necessary to reduce the loss of accuracy of the absolute value of the acquired force peaks. The experimental modelling aimed, in fact, to analyse the wave loading on a vertical structure with an overhanging horizontal cantilever slab, based on the correlation between the kinematics of breaking waves and the height, distribution, duration and characteristics of the wave impacts. For it, a proper measurement system (namely piezoelectric sensors) and high sampling frequency were required.

Instead, in our work we are not interested in the exact absolute peak value but in the relative difference or error between experimental and numerical modelling. Resampling the time series but preventing to cut off the force peaks completely (analysis that was accurately carried out), allow us to a more reliable comparison since it was not feasible to increase further the numerical sampling frequency, for data storage limitation.

4. In Figure 3, the 2ed to 5th wave profiles predicted by SPH have a gap from the right wall, which does not seem real. Please explain why.

The reviewer is right. The gap observed between the right wall and the fluid is created because of the high repulsion mechanism created with the Dynamic Boundary Conditions (DBC) implemented in DualSPHysics (in the order of 1.3 times the smoothing length as shown in Domínguez et al., 2015). This approach presents several pros and cons; the disadvantages come from the high repulsive force resulting in a separation distance (GAP) and the advantages are the easy implementation, the application to arbitrary 2-D and 3-D geometries and good validation obtained in many coastal engineering problems using DBC.

In this paper we have not described in detail neither the boundary conditions of IHFOAM, nor the condition in DualSPHysics. More information about DBC can be found in [39] and [40]. Following the suggestion of the reviewer we have added the following text:

“The gap observed between the right wall and the fluid in Figure 3 (left column) is due to the high repulsion mechanism created with the Dynamic Boundary Conditions (DBC) implemented in DualSPHysics (~ 1.3 times the smoothing length as shown in [40]).”

5. In the paragraph after Figure 4, why the authors emphasis "wave reflection"? In experiments, there are wave reflections. The full scale numerical model should be able to capture the reflection effect. Unless some devices were used to absorb wave reflection in the experiments, the discrepancies should not be attributed to wave reflections.

Indeed, the current version of DualSPHysics model is capable to handle wave reflection (see Altomare et al. 2017). However here the problem is not the reflection itself but the way the reflected waves are absorbed. The numerical model implements a technique based on near-field wave gauge and linear shallow water theory to compensate the reflected waves reaching the numerical piston type wavemaker (more details in Altomare et al. 2017). Meanwhile 2 far-field wave gauges are used in the experimental tests with the application of digital FIR filters (see Frigaard and Christensen, 1994). The two systems might lead to slightly different response of the experimental and numerical wavemakers. Due to the already mention stochastic nature of the impact events, the aforementioned difference will definitely heighten the differences in the wave loading time series.

Therefore, we have modified the text according to this:

“The absorption systems in the experimental flume and in the numerical tank are not the same, so that, the efficiency to absorb wave reflection is also different, which leads to differences in the free-surface elevations, accordingly in the time series of the wave loading.”

6. In the 5th line of the paragraph after Figure 4, what does the sentence "That interval starts, for each of the wave sensors" mean?

It refers to the beginning of the temporal window selected for comparison. The paragraph has been adjusted according to the issue raised by the reviewer as follows:

“In order to avoid re-reflection effects in the sensitivity analysis of the free-surface elevation, only a temporal window of 20 seconds was analysed for all the time series. In this specific case, the beginning of this window corresponds to the instant when the first wave reaches the first sensor.”

7. In the last paragraph of page 10, the discussions can be improved from several aspects:

7.1) the standard derivation of the experimental force may be because the force is computed by the integration of pressure values at several locations. A more convincing way is to compare the pressure values directly. This is feasible because there is data for pressure;

It was verified that the standard deviation of the experimental force does not depend on the fact that the force is computed by the integration of pressure values at several locations, but it is related to the stochastic nature of the impact: generating the same wave time series leads to the differences (no full repeatability of the force results).

7.2) the second peak in quasi-static stage of the expt. result is not obvious. It may be filtered out by the used sampling scheme. Or the sensors did not capture it. Or this phenomenon does not appear in the particular case. A more rigorous discussion would help;

About the capability of the sensors to capture the quasi-static impact, we refer to what stated in paragraph 3.1.:

“The accuracy of the acquired pressures depends on the measurement type selected for charge amplifier used for the Kistler sensors (dynamic or quasi-static) and the kind of loading exerted on them. Depending on the combination of exerted loading and measurement type, a drift can be seen in the output signal. This drift was noticed in the pressure signal acquired during the tests carried out at Ghent University: it was only corrected in post-processing, fact that can introduce some inaccuracies in the measurements of the experimental quasi-static pressures.”

7.3) in the third sentence of page 11, it says "This high value of the standard deviation could be a sign of the lack of ability of the Kistler sensors to reproduce the quasi-static force". Are there any solid evidences? If not, it is normally unusual to question the benchmark data;

We are not questioning the experimental data. We are only underlining the limitations of measurement system to allow a fairer comparison.

7.4) the IHFOAM captures the peak force better. This is more important because the peak forces are used in engineering design. It would be suggested to present the snapshots when the peak force and quasi-static peak happen, to support the discussions here;

We only analysed averaged impacts, therefore, there are no snapshots corresponding to these impacts available.

8. The pressure on the horizontal part of the structure is not discussed. No need to present them in the figures and text.

We have removed all figures and text related with the pressure on the horizontal part.

9. This study only compares the accuracy of SPH and OpenFoam in predicting the macro-scale parameters (i.e. wave elevation and force). The conclusion "mesh-free methods have achieved the required level of maturity in comparison with the more established mesh-based methods" seems to be much broader.

We have modified the text according to the comment of the reviewer:

“mesh-free methods have achieved the required level of maturity in comparison with the more established mesh-based methods in predicting the macro-scale parameters (i.e. wave elevation and force).”

10. The authors have concluded that the accuracy of OpenFoam is slightly better in general. It would be better to comment (or indirectly compare) on the computational efficiency, since the computational efficiency is a weak point for particle method. If being less accuracy and slower, what are the reasons to choose a particle method?

We agree with reviewer, so that we have included this sentence:

“For the present case under study, IHFOAM provides the most reliable and efficient solution. However, SPH model can be more suitable to solve problems that involve large free-surface deformations since there is no mesh distortion, rapidly moving complex geometries or the interfaces of multiphase flows.”.

References:

Altomare C, Domínguez JM, Crespo AJC, González-Cao J, Suzuki T, Gómez-Gesteira M, Troch P. Long-crested wave generation and absorption for SPH-based DualSPHysics model. *Coastal Engineering* 2017; 127: 37-54. doi: 10.1016/j.coastaleng.2017.06.004.

Domínguez JM, Cercos-Pita JL, Fourtakas G, Crespo AJC, Vacondio R, Rogers BD. Evaluation of reliability and efficiency of different boundary conditions in the same SPH code. 10th SPHERIC International Workshop, Parma, Italy, 2015.

Frigaard P, Christensen M. An absorbing wave-maker based on digital filters. *Proc. 24th Int. Conf. Coast. Eng.* 1994; 168-180.

Shao S, Gotoh H. Turbulence particle models for tracking free surfaces. *Journal of Hydraulic Research* 2005; 43(3): 276-289.

Highlights

The capability of DualSPHysics to reproduce violent wave impacts is assessed.

The efficiency and reliability of DualSPHysics are compared with a meshbased model.

DualSPHysics and IHFOAM show a similar performance.

Meshless methods attain the level of maturity to be used for engineering purposes.

The combined use of both kind of models overcome the limitations of each approach.

On the accuracy of DualSPHysics to assess violent collisions with coastal structures

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Abstract

The accuracy of DualSPHysics and IHFOAM to reproduce the propagation of a regular wave train and its collision with a vertical sea wall with a hanging horizontal cantilever slab was compared by different metrics (skill index, normalized standard deviation, correlation coefficient and root-mean square error). These metrics were applied to elevation of the free-surface and to the horizontal force exerted on the wall. The numerical results of both models converge to experimental values when increasing the resolution, being the accuracy similar for both models at high spatial resolution, although IHFOAM has a slightly higher performance than DualSPHysics for low and medium resolutions. Overall, the analysis suggests that mesh-less models have attained the level of maturity required to provide results with an accuracy equivalent to mesh-based models.

Keywords: SPH, DualSPHysics, mesh-based models, IHFOAM, accuracy, convergence.

1. Introduction

Understanding the laws that rule extreme hydrodynamic processes requires an in-deep analysis of their intrinsic characteristics. For this purpose, either physical or numerical modelling are employed. In general, physical model tests constitute the most used approach for analysis purposes despite being costly, time consuming and strongly dependent on the accuracy of the measurement equipment. As an alternative numerical models are shown as a useful complementary option to be used in a wide range of practical applications. One of the main advantages of numerical modelling is its capability to simulate any scenario with reduced costs. Moreover, numerical models do not suffer from scale effects and can provide information on physical quantities that

could be difficult to measure in scaled models or in prototypes. In general, there are two main methodological approaches to numerical modelling: mesh-based and mesh-free approaches. Traditionally, computational techniques are based on the mesh-based approach. The mesh-based models, also called Eulerian models, discretise the domain using some type of mesh to analyse the variable of interest at fixed nodes by solving the governing equations by means of some numerical methodologies as, for example, finite differences, finite elements or finite volumes techniques. These methods have shown to be robust and reliable although they require, in some cases, expensive mesh generation and have severe technical challenges associated with implementing conservative multi-phase schemes. The mesh-free models, also called Lagrangian models, discretise the domain in particles and analyse the variables of study by following these particles. These methods allow overcoming part of the drawbacks that characterise the mesh-based schemes. However, these methods have their own limitations, mainly associated to the lack of completeness of the kernel functions. In addition, the computational cost is usually higher than associated to mesh-based methods. Approaches such as the Smoothed Particle Hydrodynamics (SPH) technique [1], Monte Carlo methods [2] or the particle finite element method (PFEM) [3] are examples of mesh-free schemes. In the particular case of SPH-based models large deformations can be efficiently treated since there is no mesh distortion due to the Lagrangian nature the method. This property makes SPH an ideal technique to study highly non-linear phenomena as, for example, violent free-surface motion. In addition, the structure of the SPH algorithms allows their easy adaptation to GPU cards, which alleviates the computational costs associated to the method.

SPH method was developed originally for astrophysics in the 1970s [4, 5]; since then, SPH has been successfully applied to several fields of engineering as solid mechanics [6, 7, 8] or Computational Fluid Dynamics (CFD) [9, 10]. Li and Liu [11] and Violeau [1] show a review of some mesh-free methodologies and their applications. In SPH the continuum is replaced by particles, which move according to the governing dynamics. Differently from Eulerian methods, for whom the free-surface elevation is obtained using volume of fluid methods (VOF), no special tracking is needed in SPH to detect the free surface and, as mentioned before, the domain is multiply-connected due to the Lagrangian nature the method. Thanks to these properties, SPH has been used to describe a wide variety of free-surface flows like flooding scenarios [12], wave propagation over a beach [13], fluid-structure interaction [14, 15, 16, 17, 18, 19], dam breaks [20] and problems involving sloshing dynamics [21]. During the last decade SPH has been widely applied to coastal engineering [22, 23, 24, 25, 26, 27, 28]. St-Germain et al. [29] used SPH to investigate the hydrodynamic forces induced by the impact of rapidly advancing tsunamis. These previous works showed that SPH-based models have achieved a high level of accuracy to be successfully compared with experiments. However, as far as we know, only a few works have dealt with the convergence of SPH results to experimental measurements in terms of the spatial resolution [30] or the comparison between mesh-free and mesh-based models have been analysed in detail [31]. Furthermore, Neves et al. [32] compared the time series of free-

surface elevation and horizontal velocity for IHFOAM and DualSPHysics and Židonis and Aggidis [33], studied the benefits and drawbacks of different mesh-based and mesh-free codes to simulate Pelton turbines.

In the present work, the accuracy of DualSPHysics and IHFOAM to simulate wave impacts on a particular coastal structure will be compared. Both models will be used to reproduce the experimental data described in Kisacik et al. [34].

The paper is organized as follows. First a brief description of the numerical models DualSPHysics and IHFOAM is shown. Then the experimental and numerical setups are presented along with the statistical tools used to analyse the results. Finally, results on the wave shape development near the structure, the free-surface elevations along the flume and the horizontal force exerted onto the vertical part of the structure are compared.

2. Numerical models

2.1. DualSPHysics model

DualSPHysics is a numerical model based on the Smoothed Particle Hydrodynamics (SPH) method. A complete description of DualSPHysics can be found in [35]. SPH is a Lagrangian and mesh-less method where the fluid is discretised into a set of particles that are nodal points where physical quantities (such as position, velocity, density, pressure) are computed as an interpolation of the values of the neighbouring particles. The contribution of these neighbours is weighted using a kernel function (W) that measures that contribution starting from the initial particle spacing. This distance between particles is normalized using the smoothing length (h_{SPH}), which is the characteristic length that defines the area of influence of the kernel. The kernel presents compact support, so that the contribution of particles beyond a cut-off distance (here $2h_{SPH}$) is not considered.

The mathematical fundamentals of SPH are based on integral interpolants. Any function F can be computed by the integral approximation.

$$F(\mathbf{r}) = \int F(\mathbf{r}') W(\mathbf{r} - \mathbf{r}', h_{SPH}) d\mathbf{r}' \quad (1)$$

This function F can be expressed in discrete form based on particles. Thus, 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:

$$F(\mathbf{r}_a) \approx \sum_b F(\mathbf{r}_b) W(\mathbf{r}_a - \mathbf{r}_b, h_{SPH}) \frac{m_b}{\rho_b} \quad (2)$$

where the volume associated to the neighbouring particle b is m_b/ρ_b , being m and ρ mass and density respectively.

The discrete SPH system of equations of a weakly compressible fluid is, according to [36]:

$$\begin{cases} \frac{d\rho_a}{dt} = \sum_b m_b (\mathbf{v}_a - \mathbf{v}_b + \Psi_{ab}) \nabla_a W_{ab} \\ \frac{d\mathbf{v}_a}{dt} = - \sum_b m_b \left(\frac{P_b + P_a}{\rho_b \rho_a} + \Pi_{ab} \right) \nabla_a W_{ab} + \mathbf{g} \\ \frac{d\mathbf{r}_a}{dt} = \mathbf{v} \end{cases} \quad (3)$$

where t is time, $\mathbf{r}$ position, $\mathbf{v}$ velocity, P pressure, ρ density, m mass, $\mathbf{g} = (0, 0, -9.81)$ m/s² the gravitational acceleration and W_{ab} the kernel function that depends on the distance between particles a and b . One option is the Quintic kernel [37] where the weighting function vanishes for initial particle spacing greater than $2h_{SPH}$. Π_{ab} is the viscous term according to the artificial viscosity proposed in [36]. Ψ_{ab} is the diffusion term introduced in the so called delta SPH approach proposed by Molteni and Colagrossi in [38].

The system is closed with the Tait's equation of state that allows computing pressure from density values

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

where $\gamma=7$ is the polytropic constant and $B=c_0^2 \rho_0 / \gamma$, being ρ_0 the reference density and c_0 the numerical speed of sound.

Dynamic Boundary Conditions (DBC) were used following [39] and [40]. Waves were generated by means of moving boundaries that mimic the movement of a wavemaker in a physical facility. In the present study, a piston-type wavemaker that moves with a pre-imposed displacement was considered to generate monochromatic and random waves. In addition, an active wave absorption technique was applied to prevent re-reflection at the piston. Details on wave generation and absorption can be found in [41].

2.2. IHFOAM

IHFOAM [42, 43] will be considered here for comparison purposes, so a shallow description of the model will be provided. IHFOAM is a mesh-based numerical model that uses the volume of fluid discretization method (VOF) to solve the Reynolds averaged Navier-Stokes (RANS) equations for two incompressible phases (water and air). IHFOAM derives from a more general numerical model named OpenFOAM® by using the solving procedure *interFoam* included in the latter one. Besides, the code IHFOAM improves the capability of OpenFOAM® for wave generation and active

wave absorption by adding new boundary conditions avoiding the definition of moving boundaries. The use of moving boundaries increases the computational time since the mesh has to be redefined every time step. For a more detailed explanation of wave generation and absorption methods, the reader is referred to [44].

3. Case of study

3.1. The physical model

The physical model tests were carried out in the wave flume ($30\text{ m} \times 1\text{ m} \times 1.2\text{ m}$) of Ghent University (Belgium). A vertical structure with horizontal cantilever slab was located 22.5 m away from the wavemaker on a uniform slope ($1/20$). The structure was 0.3 m high and 0.6 m long. A series of flush-mounted Kistler sensors were used to measure wave impact pressures. These sensors are based on the piezoelectric measurement principle: the force acting on the highly sensitive transversal measuring element generates a proportional charge at the signal output. The accuracy of the acquired pressures depends on the measurement type selected for charge amplifier used for the Kistler sensors (dynamic or quasi-static) and the kind of loading exerted on them. Depending on the combination of exerted loading and measurement type, a drift can be seen in the output signal. This drift was noticed in the pressure signal acquired during the tests carried out at Ghent University: it was only corrected in post-processing, fact that can introduce some inaccuracies in the measurements of the experimental quasi-static pressures. Eight wave gauges were used to measure the free-surface elevation along the flume. The three first wave gauges (WG1, WG2 and WG3) were located in the part where the slope of the bottom of the wave flume is equal to zero and far from the structure while the rest of wave gauges (WG8, WG4, WG5, WG6 and WG7) were located near the structure and in the part where the slope is equal to $1/20$. The distances from the wavemaker to the different wave gauges were 11.32, 11.81, 12.50, 20.59, 20.86, 21.25, 21.50 and 21.85 m. In addition a high speed camera (HSC) was used to record the dynamics of the wave breaking mechanism.

A sampling frequency of 20 kHz was used for pressure recording, despite the fact that a frequency of 6 kHz was already enough to avoid reduction of the peak pressures [45]. The free-surface elevation was sampled at 40 Hz. Figure 1 shows a schematic view of the model including the position of the wave gauges and the pressure sensors. In this work the pressure sensors located at the vertical wall of the structure were considered to compute the horizontal forces exerted onto the structure.

The water depth was equal to 0.605 m near the piston, and 0.105 m near the structure. The wave height and wave period of the generated wave were 0.065 m and 2.2 s, respectively. An in-depth description of the full set of the physical tests is shown in [34].

Figure 1. Setup of the experiment.

3.2. Numerical setup

In DualSPHysics, the numerical tank is created with a pre-processing tool that allows generating particles starting from any type of complex geometry. This tool employs a 3-D Cartesian lattice to locate particles. The idea is to build any object using particles. These particles are created at the nodes of the 3-D Cartesian lattice. First, the lattice nodes around the object are defined and then particles are created only at the nodes needed to draw the desired geometry. Only the initial size of the lattice needs to be defined which will be the initial inter-particle spacing, dp .

IHFOAM is a mesh-based method where the numerical domain is initially meshed by using a mesh generator tool as, for example, Gmsh [46]. The defined mesh will be a set of cells with a characteristic length equal to dl . The initial inter-particle spacing of DualSPHysics (dp) is similar to the characteristic length of cells of the mesh (dl) and the number of particles of DualSPHysics is close to the number of cells of IHFOAM. Therefore, the spatial resolution of both numerical models can be considered as equivalent.

Figure 2 shows an example of the discretisation of a square box of size L with a water depth equal to h using DualSPHysics and Gmsh. The initial particle spacing defined with DualSPHysics is equal to dp leading to N_p particles of water and the characteristic length of the mesh cells of IHFOAM is equal to dl leading to N_c cells. Most of them correspond to the water phase and only a few to the air phase.

Figure 2. Discretization of a square domain of size L with a water height of h using DualSPHysics and IHFOAM. N_p particles and N_c cells are used respectively.

A physical time of 70 seconds was simulated by both models and a sampling frequency of 100 Hz was used both for force and free-surface elevation. The experimental sampling frequency in experiments was resampled according to the numerical one.

The reliability and the accuracy of DualSPHysics and IHFOAM is compared using six different spatial resolutions. Table 1 summarises the characteristic length (L_c) of both numerical methods, the number of particles of DualSPHysics and the number of cells of IHFOAM defined for this analysis.

Table 1. Characteristic lengths, number of particles and cells of DualSPHysics and IHFOAM, respectively, for each spatial resolution.

Finally, waves were generated in different ways in both numerical models. DualSPHysics generates the desired waves by means of moving boundaries that move accordingly to real displacement of the piston-type wavemaker employed during the physical tests. Piston-type wave generation techniques in DualSPHysics have been

discussed and their accuracy demonstrated in [47]. By contrast, IHFOAM generates waves starting from the real displacement of the experimental wave generator but without using moving boundaries [48].

Although DualSPHysics simulations can be executed both on CPUs and GPUs, the computational time needed to run the case with the CPU version is considerably higher (~20 times) than with the GPU version. We should note that DualSPHysics is mainly optimized to be run on GPUs and the CPU version is mainly kept for development purposes. Therefore, DualSPHysics simulations were run on a GPU card NVIDIA Titan Black and IHFOAM simulations on an Intel Xeon E5-2640 (using 16 physical cores).

3.3. Methods

Different metrics will be used to assess the accuracy of the numerical results. Two variables will be considered: free-surface elevation and the force exerted onto the vertical wall.

The horizontal force on the vertical wall was not measured during the physical model tests. Instead, the pressures measured at 7 different locations (Figure 1) were integrated. Therefore, the force to be compared with numerical results will be computed from that pressure using Eq. (5).

$$F_h(t) = \frac{1}{2} \sum_{k=1}^{M-1} [p_k(t) + p_{k+1}(t)](z_{k+1} - z_k) \quad (5)$$

where M is the number of pressure sensors in the vertical wall (equal to 7), $p_k(t)$ is the value of the pressure at sensor k at time t and z_k is position in z of the k sensor, $p_{k+1}(t)$ and z_{k+1} are the same but for sensor $k+1$.

The agreement between and experimental results [34] is quantified in terms of their normalised standard deviation (σ_n), centred root-mean-square difference (E_n) and correlation (R).

$$\sigma_{n,A} = \frac{\sqrt{\frac{\sum_{i=n}^N (A_i - \bar{A})^2}{N}}}{\sigma_B} \quad (6)$$

$$E_{n,A} = \frac{\sqrt{\frac{\sum_{i=n}^N [(A_i - \bar{A}) - (B_i - \bar{B})]^2}{N}}}{\sigma_B} \quad (7)$$

$$R_A = \frac{\sum_{i=n}^N [(A_i - \bar{A})(B_i - \bar{B})]}{N \sigma_A \sigma_B} \quad (8)$$

where A is a generic variable and B a reference variable. The subscript i refers to the different samples, N is the number of samples, barred variables refer to mean values and σ is the standard deviation calculated as

$$\sigma_B = \sqrt{\frac{\sum_{i=1}^N (B_i - \bar{B})^2}{N}} \quad (9)$$

These variables will be group together in Taylor's diagrams [49].

In addition, other metrics will also be considered as the accuracy index (AI), defined as the sum of $|1-R^2|$ and E_n . Note that both variables tend to zero when the agreement between numerical and experimental is perfect, in such a way that small AI values mean good accuracy.

Finally, the skill index

$$S_A = \frac{4(1+R_A)^4}{\left(\sigma_{n,A} + \frac{1}{\sigma_{n,A}}\right)^2 (1+R_0)^4} \quad (10)$$

was also defined, where R_0 is the maximum correlation attainable for the model (equal to 1 in this case). The index S can range from 0, in the case of models with no skill to reproduce the experimental observations, to 1, for models with a high skill to reproduce the experiments. AI is based on the correlation and the centred root-mean-square difference while S is based on the correlation and the standard deviation. Therefore, both indices are complementary.

4. Results and discussion

4.1. Wave shape development

A visual comparison between the wave shape development obtained from simulations and from experimental tests is shown in Figure 3. Red dots represent the experimental free-surface profile observed in the physical tests [34]. The three instants immediately before the collision on the horizontal part of the structure show a good agreement between the physical model test and both numerical models. The impact on the top of the structure takes place at Time= 34.58 s for DualSPHysics and Time= 34.43 s for IHFOAM and is properly reproduced by both models. After the impact, the fluid in DualSPHysics splashes back and propagates downwards while the water phase in IHFOAM goes backwards and remains stuck to the horizontal part of the structure. These differences are related to the different approaches to define the boundary conditions in both numerical models and to the existence of air phase in IHFOAM model, which is not considered in DualSPHysics. Experimental results show an intermediate behaviour after the impact since part of the water is stuck to the horizontal

roof and the rest splashes back. After the impact on the horizontal part of the structure both numerical models show a slight deviation from the experimental tests. Despite these differences, it can be concluded that both DualSPHysics and IHFOAM reproduce, at least visually, the dynamics of the wave breaking mechanism observed in the physical tests.

The gap observed between the right wall and the fluid in Figure 3 (left column) is due to the high repulsion mechanism created with the Dynamic Boundary Conditions (DBC) implemented in DualSPHysics (~ 1.3 times the smoothing length as shown in [40]).

Figure 3. Different snapshots of the DualSPHysics and IHFOAM simulations compared with the experimental wave profiles (red dots).

4.2. Sensitivity analysis of the numerical models to spatial resolution

Figure 4 shows the time series of the free-surface elevation at all wave gauges obtained in the experiments with both numerical models and using resolution Res2 (see Table 1).

Figure 4. Time series of free-surface elevation measured at all wave gauges obtained in the experiment (green dashed line), with DualSPHysics (red solid line) and with IHFOAM (blue solid line).

The visual comparison of the time series of the free-surface elevation depicted in Figure 4 shows the good agreement between numerical and experimental results once re-reflexion effects were neglected. The absorption systems in the experimental flume and in the numerical tank are not the same, so that, the efficiency to absorb wave reflection is also different, which leads to differences in the free-surface elevations, accordingly in the time series of the wave loading. In order to avoid re-reflection effects in the sensitivity analysis of the free-surface elevation, only a temporal window of 20 seconds was analysed for all the time series. In this specific case, the beginning of this window corresponds to the instant when the first wave reaches the first sensor. Figure 5 shows the Taylor's diagram of free-surface elevation averaged at all wave gauges. Experimental results were used as reference (marked Ref in the diagram) to analyse the effect of spatial resolution on the accuracy of the numerical models. In general, the accuracy of both numerical models increases with the spatial resolution. The best correlation (~ 0.99) is obtained with Res1 for both numerical models. The correlation of the remaining spatial resolutions ranges from ~ 0.9 for Res2 to ~ 0.8 for Res6. A similar behaviour is observed for the values of centred root-mean-square difference. The values of centred root-mean-square difference obtained for Res1 are close to 0.2 for both models, and they range from ~ 0.5 for Res2 to ~ 0.6 for Res6. The value of the normalised standard deviation obtained for Res1 and Res2 is close to 1. Then it drops reaching a value of 0.8 for Res6. The value of normalised standard deviation obtained in the analysed cases is always less than 1. That means that both numerical methods underestimate the amplitude of the oscillations of the experimental case. For each

spatial resolution, the accuracy obtained with IHFOAM is slightly better than obtained using DualSPHysics.

Figure 5. Taylor’s diagrams of the free-surface elevation averaged at all wave gauges. DualSPHysics results are marked with red dots and IHFOAM results with blue dots. The experimental series is marked with a black dot and labeled (Ref).

Table 2 shows that skill index of η obtained with DualSPHysics (S_D) and IHFOAM (S_I). It can be seen that the values of S increase with the resolution and they are close to one for high spatial resolutions (Res1). For each analysed resolution, the values of S obtained with IHFOAM are similar to the values obtained with DualSPHysics, although slightly better, except for Res5.

Table 2. Skill index of the averaged values of free-surface elevation. Values in brackets refer to the difference (%) between the values of S obtained with IHFOAM and the values obtained with DualSPHysics.

Figure 6 shows $|1-R_\eta|^2$ and E_η calculated for free-surface elevation and averaged for all wave sensors. The lower panel corresponds to the accuracy index (AI).

Figure 6. Averaged values of $|1-R_\eta|^2$ (upper panel), E_η (middle panel) and accuracy index (lower panel), obtained for the free-surface elevation as a function of the characteristic length (L_c). DualSPHysics (red dots) and IHFOAM (blue dots). The experimental series were considered as the reference.

For any resolution, the accuracy obtained with IHFOAM, is slightly better than obtained with DualSPHysics for the same resolution. The accuracy of both numerical methods is similar for high spatial resolution (low values of characteristic length).

The sensitivity analysis of the horizontal force exerted onto the vertical part of the structure was carried out by averaging the first 7 impacts recorded in the numerical time series and in the experimental data. Again, the experimental data was considered as the reference value. Figure 7 shows the averaged impact for both numerical methods using Res2 and in the physical tests (left panel). A schematic view of a “church-roof” type impact [50] is also shown (right panel). The shaded area of the left panel corresponds to three times the standard deviation of the experimental data. Although for numerical results there is some variability from peak to peak, its standard deviation is much less than that associated with the experimental results and was not represented with a shadow area in Figure 7 for the sake of clarity. The averaged force obtained with both numerical models resembles each other but it shows slight differences with the experimental one. Both numerical models reproduce the quasi-static force (F_{h,max_qs}) in a similar way ($\sim 185 \text{ Nm}^{-1}$). This quasi-static force is not so evident in the experimental data but it is close to 137 Nm^{-1} . The standard deviation of the experimental data for t close to 0.5 s (time of quasi-static force, t_4) reaches its maximum value. This high value of the standard deviation could be a sign of the lack of ability of the Kistler sensors to reproduce the quasi-static force. The maximum dynamic force (F_{h,max_imp}) obtained with IHFOAM is greater than the value obtained with DualSPHysics ($\sim 280 \text{ Nm}^{-1}$ and ~ 225

Nm^{-1} , respectively). The maximum dynamic force obtained from the experiments is close to 275 Nm^{-1} . The maximum dynamic force is greater than the quasi-static force in all cases although the criterion for impulsive loads based on the ration between maximum forces, $F_{h,max_imp}/F_{h,max_qs} \geq 2.5$ defined in [51], is not verified. This ratio is 1.2 and 1.5 for DualSPHysics and IHFOAM, respectively and 2.0 for the experimental force, which denotes that the analysed wave is a transitional wave between a standing wave and the loading case as defined in [52], being equivalent to the slightly breaking wave with small air trapped (BWSAT) defined in [34]. In addition to this, the experimental data shows negative values not observed in the numerical time series. This effect is due again to the working conditions of the Kistler sensors used in the experiments. This effect and the lack of ability of the pressure sensors to reproduce the quasi-static force suggest that Taylor's diagrams are not a well suited metrics for a statistical analysis of the forces exerted onto the structure. Finally, the rise time ($t_r = t_2 - t_1$), the duration of the impact ($t_d = t_3 - t_1$) and the instant of maximum quasi-static force (t_4) obtained with both numerical models are similar to the experimental ones.

Figure 7. Mean impact onto the vertical part of the structure (left panel) obtained in the physical test (black line), with DualSPHysics (red line) and with IHFOAM (blue line) using the resolution Res2. The shaded area on the left panel corresponds to three times the standard deviation of the experimental data. Schematic view of a church-roof type impact described in [50] (right panel).

Figure 8 shows $|1 - R_{Fh}^2|$, E_{Fh} and AI for the force exerted onto the vertical part of the structure. The three metrics decrease when the spatial resolution increases showing that numerical results converge to the experimental ones when the spatial resolution increases (characteristic length decreases). In general, the accuracy of IHFOAM is slightly better than obtained with DualSPHysics for mid and low resolutions, although both models are similar at high resolutions. The dashed lines shown in the lower panel represent the AI parameter calculated for the experimental signal when compared with itself considering the uncertainties. Thus the lower line was obtained by comparing $F_{h,exp} - \sigma$ and $F_{h,exp} + \sigma$ and the upper line by comparing $F_{h,exp} - 2\sigma$ and $F_{h,exp} + 2\sigma$. It is evident that, both models achieve the maximum expected accuracy at high resolution.

Figure 8. $|1 - R_{Fh}^2|$ (upper panel), E_{Fh} (middle panel) and AI (lower panel), for the numerical force exerted onto the vertical part of the structure. DualSPHysics (red dots) and IHFOAM (blue dots). Experimental results were used as reference.

5. Conclusions

The accuracy of a mesh-less model (DualSPHysics) and a mesh-based model (IHFOAM) to reproduce the experimental data obtained from the physical tests described in [34] have been compared. The experimental setup corresponds to the propagation of a regular wave train and its collision with a vertical sea wall with a

hanging horizontal cantilever slab. Free-surface elevation and the horizontal force exerted onto the wall were the variables chosen for comparison.

Different metrics were used to analyse the level of accuracy of every model. Both DualSPHysics and IHFOAM were able to reproduce wave propagation and collision with the coastal structure in a similar way. Overall, the accuracy is higher for water elevation than for forces, mainly due to the difficulty of measuring forces adequately in the experiments and to the stochastic nature of the wave impacts. Both numerical models provided a similar level of accuracy for high spatial resolution, although IHFOAM slightly outperformed DualSPHysics for low and medium spatial resolutions. Numerical free-surface elevation and forces convergence to the experimental ones as the spatial resolution increases. In summary, for the case under study, a meshless method like DualSPHysics is slightly worse in terms of accuracy and comparable in terms of performance than a state-of-the-art mesh-based model like IHFOAM. This is a remarkable fact since a decade ago the emerging models based on SPH technique were considered to be merely toy models that could be only used for oversimplified geometries (e.i.: [13] and [53]).

Therefore, the present work has demonstrated that for problems involving violent collisions with coastal structures mesh-free methods have achieved the required level of maturity in comparison with the more established mesh-based methods in predicting the macro-scale parameters (i.e. wave elevation and force).

This conclusion can be extended to other configurations although with slight peculiarities depending on the case. Mesh-based models like IHFOAM can easily include two phases with very different values of density (water and air) and are accurate even for low spatial resolution. In addition, these models allow variable spatial resolution at each node in a natural way. However, the simulation of mobile objects is not straightforward. Models based on SPH technique like DualSPHysics show lower accuracy when dealing with multiphase problems. Nevertheless, these methods are especially well suited to deal with boundaries that move rapidly or with floating objects. For the present case under study, IHFOAM provides the most reliable and efficient solution. However, SPH model can be more suitable to solve problems that involve large free-surface deformations since there is no mesh distortion, rapidly moving complex geometries or the interfaces of multiphase flows. The combined use of both kind of models is then advisable to overcome the limitations inherent to each approach and to take advantage of their strengths.

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Table 1. Characteristic lengths, number of particles and cells of DualSPHysics and IHFOAM, respectively, for each spatial resolution.

Spatial resolution	Characteristic length (mm)	Number of particles of DualSPHysics	Number of cells of IHFOAM
Res1	2	2,770,188	2,758,054
Res2	3	1,228,055	1,199,276
Res3	6	301,688	298,462
Res4	9	133,676	130,344
Res5	12	76,123	74,078
Res6	18	32,400	33,494

Table 2. Skill index of the averaged values of free-surface elevation. Values in brackets refer to the difference (%) between the values of S obtained with IHFOAM and the values obtained with DualSPHysics.

	S_D : Skill index of DualSPHysics	S_I : Skill index of IHFOAM	$\frac{S_I - S_D}{S_I}$ (%)
Res1	0.96	0.97	1.0 %
Res2	0.75	0.77	2.6 %
Res3	0.73	0.76	3.9 %
Res4	0.72	0.76	5.3 %
Res5	0.73	0.71	-2.8 %
Res6	0.66	0.71	7.0 %

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DualSPHysics

IHFOAM

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