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## Optimized hybrid model for coastal safety assessment

Source generation in DualSPHysics model, 2nd-year Progress Report

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# Optimized hybrid model for coastal safety assessment

## Source generation in DualSPHysics model, 2nd-year Progress Report

Suzuki, T.; Altomare, C.; Peeters, P.; Mostaert, F.



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## Abstract

The present document represents a progress report of the second year of the 15\_009 project on "Optimized hybrid model for coastal safety assessment".

Main aim of the first year was the implementation of an efficient, simple and accurate wave generation, wave absorption technique and active wave absorption system (AWAS) in DualSPHysics code as stand-alone model. DualSPHysics model is now able to generate both long-crested monochromatic and random waves with a piston-type wavemaker. The 1<sup>st</sup> year research reveals that AWAS is effective for monochromatic and random waves.

On the other hand AWAS is based on linear theory, therefore it is theoretically not applicable to the region where non-linearity is dominant, e.g. breaking zone. However, to decrease computational cost of the coupling model, the coupling point needs to be in the breaking zone (e.g. coupling point closer than -5 m TAW point).

In order to tackle this problem, we explored the applicability of "wave absorption for hybridization" (AWAS-hy) method in the 2<sup>nd</sup> year research.

In this report, the implementation and validation results are presented. In the validation, it was concluded that the source generation method (SG) based on Ni and Feng (2013) is applicable to the most critical condition (highly reflective condition).

This report summarizes the  $2^{nd}$  year research and gives suggestions for the  $3^{rd}$  year research.

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## 1 Introduction

## 1.1 Summary of 1<sup>st</sup> year

Seven different tasks have been defined for the present project, see Altomare et al. (2017): 1<sup>st</sup> year report.

In the first year, three tasks were completed.

- 1. Literature review of the existing Active Wave Absorption Systems that are used both in physical and numerical wave models.
- 2. Identification of the AWAS technique/s to be implemented in DualSPHysics as stand-alone model.
- 3. Implementation and validation of the AWAS technique/s with selected benchmark cases.

Those tasks resulted in a conference paper in SPHERIC 2015, Altomare et al (2015).

The fourth task, identification of the best strategy, has also been conducted (i.e. discussed with UVigo, Prof. Gomez-Gesteira, Dr. Crespo and Dr. Dominguez). As a conclusion, it was recommended to test Source Generation (SG) method.

4. Identification of the best strategy to absorb the re-reflected waves in the hybridized SWASH-DualSPHysics model.

### 1.2 Target of 2<sup>nd</sup> year

The main task for the second year is the implementation and validation of the selected wave generation method.

5. Implementation of the "wave absorption for hybridization" (AWAS-hy) and validation of the numerical model: this technique needs to be coupled with SWASH (SWASH output will be used to "steer" the movement of the wave maker in DualSPHysics to cancel out the reflected waves)

## 2 Second-year results

The main results achieved during the  $2^{nd}$  year of the project are here summarized.

- Source generation (SG) has been implemented in DualSPHysics as standalone model. Note that SG is the first implemented method as "wave absorption for hybridization" (AWAS-hy)
- Applicability of the source generation (SG) and absorption technique in a highly reflective condition has been tested.
- The SG and absorption technique is applicable in the most critical case, namely in the highly reflective condition.
- SG is using analytical solution as an input. In this study, SG is extended to be able to use SWASH output as an input (SG-SWASH).

Those have been converted into a conference paper SPHERIC 2017, Usui et al (2017), see appendix A.

Additional outcomes/activities are shown as follows.

- SWASH workshop was held in Ourense campus, Vigo University. The contents are attached in appendix B.
- Abstract for Marine2017, held in Nantes, France, in May 2017. The work entitled "Efficiency and accuracy of DualSPHysics code applied to structural design in coastal engineering: a case study from the Belgian coast" has been submitted. No full paper was requested for the conference. The abstract is shown in Appendix C.
- The 1<sup>st</sup> year's output (about AWAS) has been converted into a journal paper, and published as Altomare *et al.* (2017). This paper is attached in Appendix D

## 3 Conclusions and recommendation

SG (Ni and Feng, 2013) and SG-SWASH method have been implemented in DualSPHysics, and the applicability of those methods has been tested in a highly reflective conditions. In general, the models are capable to generate the target waves well. On the other hand, re-reflection can occur in the wave generation zone under highly reflective conditions in most of the tested conditions (7 cases reported in Usui et al., 2017) To overcome this problem, new C function has been defined in this study. The function works well by choosing the right parameter settings for Wsg, alpha and beta, for regular waves. In order to use SG and SG-SWASH method for practical engineering applications, e.g. a vertical wall case, further optimization is necessary.

However, a coupling strategy is not always necessary for such deep water conditions since standalone SPH is applicable directly: the coupling area (input for DualSPHysics) can be set at a point close to the structure and thus computational cost is limited. The purpose of the test in Appendix A was to see the performance of SG and SG-SWASH in the vertical wall condition for regular waves. As a next step, it is still necessary to check the performance of the SG-SWASH for the shallow foreshore case with irregular waves, in which a coupling strategy is necessary (shallow foreshore: large domain, irregular waves: long duration). In this case, the waves close to the structure are highly non-linear: the coupling area must be set far from the structure to reduce non-linearity and to apply either SG or SG-SWASH. However this will increase the computational cost, since the numerical domain will become larger.

Figure 1 is a sketch explaining which methodology would be applicable to the shallow foreshore case. From offshore towards the point where breaking would occur, AWAS would work very well (Altomare et al., 2017), while in the breaking zone SG-SWASH would be an option. The applicability is still to be confirmed. After the broken waves have become bores, the SG method will have problems. In that case, inlet/outlet (I/O) method can be a possible option.



The target of the 2<sup>nd</sup> year was to complete task 5 stated as below:

5. Implementation of the "wave absorption for hybridization" (AWAS-hy) and validation numerical and/or physical model results: this technique has to be specifically adjusted to be implemented as part of the hybridization algorithms (SWASH information will be again use to "steer" the movement of the wave maker in DualSPHysics to cancel out the reflected waves)

And normally the 3<sup>rd</sup> year is the last year and suppose to address three work packages below:

- 6. Optimization of the pre-processing tools required for the hybridization strategy with the intention to make it as much user-friendly as possible (e.g. the generation of the geometrical layout in SWASH and SPH has to be standardized and homogenized).
- 7. Redaction of the user manual that can guide step by step in the application of the hybridization strategy for 2D and 3D cases.
- 8. Add the transfer to Version Management as final step of integration of the model in our instrumentarium.

All the tasks of 2<sup>nd</sup> year have been conducted, however, still an important question remains. That is, how SG-SWASH works for shallow foreshore cases. It is recommended to conduct this investigation in the beginning of the 3<sup>rd</sup> year.

Apart from the SG-SWASH, a new strategy for the coupling was found during SPHERIC 2017 workshop. This method is using both mpi technique and I/O method to couple SWASH and DualSPHysics. Doing this, coupling can be 2-ways. It is also recommended to explore the possibility of implementing this mpi method to SWASH and DualSPHysics during the 3<sup>rd</sup> year of the project.

## References

Altomare, C; Domínguez, J M; Barreiro, A.; Crespo, A. J. C.; Suzuki, T; Gómez-Gesteira (2015) Numerical wave dynamics using Lagrangian approach : wave generation and passive & active wave absorption, in: SPHeric Conf., 2015.

Altomare, C; Domínguez, J M; Crespo, A. J. C.; Gonzalez-Cao, J; Suzuki, T; Gómez-Gesteira, M; Troch, P. (2017). Long-crested wave generation and absorption for SPH-based DualSPHysics model. *Coast. Eng* 127(September 2017): 37–54. doi:10.1016/j.coastaleng.2017.06.004

**Ni, X., Feng, W.B.** (2013) Numerical Simulation of Wave Overtopping Based on DualSPHysics. *Applied Mechanics and Materials* Vols 405-408 pp 1463-1471. doi:10.4028/www.scientific.net/AMM.405-408.1463.

**Usui, A., Dominguez, J., Tagliafierro, B., Altomare, C. and Suzuki, T.** (2017) Applicability of source generation (SG) and absorption technology in a highly reflective condition. *SPHERIC 2017 proceedings.* (Submitted)

## Appendix A: Applicability of source generation (SG) and absorption technology in a highly reflective condition

## Applicability of source generation (SG) and absorption technology in a highly reflective condition

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*Abstract*—Source generation (SG) and absorption technology for SPH has been implemented in DualSPHysics. SG is a numerical method in which movement of particle is controlled by a weighting function in a specified source generation domain. In the present work, the basic performance of SG is tested for a vertical wall case, which is the most critical case due to wave reflection. In addition, SG is extended to coupling with SWASH.

#### I. INTRODUCTION

SPH models are getting popular as an alternative wave-flow model in coastal engineering thanks to the development of numerical techniques and computation technologies in the last decades. However still computational cost of the SPH models is huge, even compared to one of the most expensive wave models, e.g. RANS-VOF models [1]. One of the SPH model, DualSPHysics [2] significantly improved the computational time by using GPU technique, while, still the computational cost is not little and thus it is not always easy to apply it to realistic engineering problems.

In order to overcome this drawback, a coupling with computationally less demanding wave models was introduced and proved to be useful for coastal engineering application [3]. Typically computationally less demanding models (e.g. Boussinesq models, NLSW models) are accurate for wave transformation at a reasonable computational cost but it is not very accurate for wave-structure interaction due to the simplification of some physical aspects. On the other hand, SPH models are capable to generate accurate results for both wave transformation and wave structure interaction. One drawback is that these are computationally too expensive to apply for a large domain.

Another example of the coupling is DualSPHysics and SWASH [4]. SWASH is based on Non-Linear Shallow Water equations and thus it is computationally much less demanding. The wave propagation is calculated by SWASH and wavestructure interaction is calculated by DualSPHysics. Doing that the drawbacks of the each model is overcome. However still this method cannot deal with very long time series where reflection is dominant. The reason is that the wave generator is forced to move according to the input from SWASH model, so the re-reflection J.M. Dominguez EPHYSLAB Vigo University Ourense, Spain jmdalonso@gmail.com

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can be occurred from the wave generator. To avoid re-reflection problem, number of the waves can be reduced so that re-reflection from the paddle do not reach to the target point. This problem can be solved by activating AWAS at the wave generation [5]. By this method the reflected waves do not re-reflect, or reflection is very limited at the wave paddle. Piston generation with AWAS (Active Wave Absorption System) can give reliable wave generation for long time duration.

The coupled model, DualSPHysic and SWASH with AWAS seems to be a promising model for coastal engineering application but still there is a limitation for very shallow foreshore application (e.g. [6,7]). Ideally the coupling point should be outside the breaking zone since theoretically AWAS is based on the linear theory and thus it could only be applied to non-breaking area. In principle the coupling point needs to be in the breaking zone otherwise the efficiency of the coupling model is limited.

Recently a wave generation method has been introduced in SPH ([8]). This approach is referred as Source Generation (hereafter SG). Different from Moving Boundary wave generators (hereafter MB) such as piston-type generators, SG is a numerical method in which movement of particle is controlled by a weighting function in a specified source generation domain. Since SG is a pure numerical method, it might be applied to cases in which MB cannot be used.

The purpose of this paper is to validate SG further by implementing the concept in DualSPHysics and to discuss the applicability and limitation of this method for wave transformation which has not been fully discussed yet. To this end we use a highly reflective condition namely a vertical wall case as a bathymetry and applied mainly regular wave as wave condition. Furthermore, SG method is extended to the coupling case with SWASH, and the basic behavior is investigated.

#### II. SOURCE GENERATION

The concept idea of source generation was originally presented by [9]. Then this technique was applied to VOF, FEM and MAC (Marker-and-Cell) methods. Recently Ni and Feng developed a source generation technology suited to SPH numerical simulation

([8]). This technique consists of two parts, namely source generation and absorption.

In principle the particle velocity in the source generator is controlled by analytical solution with a weighting function C, which has the form of 1/4 cosine-shaped function (Figure 1). The velocities in the source generation are expressed as follows:

$$u_i = Cu_{ci} + (1-C)u_{pi}$$
 (1)

$$w_i = Cw_{ci} + (1 - C)w_{pi} \tag{2}$$

where  $u_i$  and  $w_i$  are the controlled horizontal and vertical velocities,  $u_{ci}$  and  $w_{ci}$  are the horizontal and vertical velocities calculated from the wave theory,  $u_{pi}$  and  $w_{pi}$  are the actual horizontal and vertical velocity calculated in the numerical model.

Damping area (i.e. passive absorption) is introduced behind the SG to eliminate un-necessary reflected waves from the rear side.



Figure 1. Model set-up of the sensitivity analysis for wave propagation.

#### III. SENSITIVITY ANALYSIS FOR WAVE PROPAGATION IN SG

Before investigating applicability of SG to the highly reflective conditions, sensitivity of key parameters for wave propagation is investigated. In order to evaluate incident waves, damping area is placed at the end of the domain. Due to this, reflection from the vertical wall at the end of the domain is eliminated and thus only generated incident waves from SG (i.e. not contaminated by reflected waves from the boundary) can be investigated. In total 24 cases were conducted for this sensitivity analysis. Five parameters which might have influence to the wave propagation have been investigated (coefdt, coefh, coefsound, dp/H, CFL). Default values used in this sensitivity analysis are, coefdt=1000, coefh=1.5, coefsound=16, dp/H=1/10 and CFL=0.2. Each coefficient is named here as it is used in the DualSPHysics input file. For further specifications, see the XML guide that is available at http://dual.sphysics.org/index.php/downloads/ and that is conceive to help the users to create an input file for DualSPHysics run in a xml format. For parameter coefdt, see, instead, Section III-B-1) of the present document.

#### A. Model setup

Basic performance of wave propagation is tested for a simple vertical wall case with damping area in regular waves (Figure 2). The bottom is flat and the wave generation is limited in a range of Stokes  $2^{nd}$  order. The wave conditions used in this sensitivity analysis correspond to H=0.1 m, T=1.6 s and h=0.8 m (L=3.45 m). Wsg, the width of the source generator, is set as 3.45 m, which is the same length as wave length (Wsg/L=1). Since the bathymetry was kept simple as such, wave properties are the same at each measurement points. Thus it is possible to compare numerical results (average of 3 wave gauges) with the theoretical values.



Figure 2. Model set-up of the sensitivity analysis for wave propagation.

#### B. Sensitivity analysis for wave propagation in SG

#### 1) Coefdt

The velocity of fluid particles in the Source Generation (SG) area is gradually corrected at each time step, so the aggressiveness of this correction depends on the number of calculation steps per dt (time between two time steps). A correction factor 'coefdt' is introduced to avoid this dependence on dt. Figure 3 shows the sensitivity of the wave generation error compared to theoretical wave height at the wave gauge for coefdt. As can be seen, error becomes very small when coefdt is 0 (coefdt is not applied) or more than 10.



Figure 3. Error of wave height and period for coef dt.

#### 2) Coefh

Coefh is a coefficient needed to compute the smoothing length, h. In detail, h=coefh\*dp\* $\sqrt{2}$  in 2D simulations. Figure 4 shows the sensitivity of the wave generation error compared to theoretical wave height at the wave gauge for coefh. As can be seen, error becomes negligible when coefh is more than 1.5.



Figure 4. Error of wave height and period for coef h.

#### 3) Coefsound

Coefsound is a coefficient needed to compute the speed of sound,  $c_0$ , at the reference density (i.e.,  $\rho_0=1000 \text{ kgm}^3$ ) where  $c_0=\text{coefsound} \cdot (g \cdot h_{swl})^{0.5}$ , being  $h_{swl}$  the still water level. Figure 5 shows the sensitivity of the wave generation error compared to theoretical wave height at the wave gauge for coefsound. As can be seen, error the error is quite limited when coefsound is between 10 and 25.



Figure 5. Error of wave height and period for coef sound.

#### 4) Non-dimensional initial particle interspace (dp/H)

Non-dimensional initial particle interspace is here defined as the ratio between the particle interspace set at the beginning of the numerical simulation, dp, and the target wave height, H. This parameter basically expresses how many fluid particles are included in one wave height, in average. Therefore, it is an important parameter for the accuracy of surface waves. Figure 6 shows the sensitivity of the wave generation error compared to theoretical wave height at the wave gauge. As can be seen, error is limited when dp/H is between 1/10-1/40.



Figure 6. Error of wave height and period for coef sound.

#### 5) CFL

In explicit time integration schemes, the time step is calculated based on Courant-Friedrichs-Lewy condition, the forcing term and the viscous diffusion term in DualSPHysics. CFL is here used as a factor to correct minimum criteria derived by the forcing term and the viscous diffusion term. Figure 7 shows time series of water surface elevations recorded at the wave gauge. As can be seen, large wave set-up is occurred when large coefficient value is used. 0.1 or 0.2 should be used to keep the mean water level stable.

#### C. Summary of the parameter study

In total 24 numerical runs have been conducted to get appropriate parameters for the wave propagation. Both wave height and wave period were compared to theoretically calculated values. The coefft and coefh show some differences in the wave height, while other cases did not show any significant differences. For wave period, none of the coefficient have a significant influence in the tested cases. One value for each parameter has been selected to apply for the numerical test cases in the section IV. The values are summarized as follows:



Figure 7. Time series by different CFL.

#### IV. APPLICABILITY OF SG METHOD IN A HIGHLY REFLECTIVE CONDITION

Applicability of SG to the highly reflective condition is investigated here. In order to judge the performance with highly reflective conditions, it must be verified that the wave are properly generated. Therefore, sensitivity of Wsg for incident waves is investigated. The value of Wsg was kept equal to one wave length in the analysis described in the previous section. The focus is now to check whether the size of the SG can be modified but achieving the same or even better accuracy. After that, the highly reflective condition cases can be executed.

#### A. Model setup

Performance of SG is tested in regular waves. The reason of using regular waves is that it is straightforward to see small influence in wave height. Figure 8 shows the model setup of the sensitivity analysis for wave generation (with damping area) and applicability test under highly reflective condition (without damping area). For the applicability test, 22 wave gauges were placed close to the right-side wall equally distributed over a length of L/2. These measurement points have been used to reconstruct the reflection pattern in front of the vertical wall. The wave conditions are changed as shown in Table I. Note that the wave condition is limited in a range of Stokes  $2^{nd}$  order (Figure 9).

#### B. Post-processing method for wave reflection

For the applicability tests (i.e. vertical wall cases), reflected waves and re-reflected waves are analysed to investigate the performance of SG. Note that the 'reflected waves' means the waves reflected one time at the vertical wall, and 're-reflected waves' includes reflection (if applicable) at the source generator. The time window of the reflected waves and re-reflected waves are shown in Figure 10.



Figure 8. Model set-up of the sensitivity analysis for wave generation and applicability test under the highly reflective condition.



Figure 9. Tested wave conditions plotted in la Maute diagram (xxxx) for wave generation and applicability test under the highly reflective condition.



Figure 10. Time window for reflected waves and re-reflected waves.

#### C. Sensitivity analysis for wave generation

Sensitivity analysis of different L/Wsg values has been carried out to assess the accuracy of the wave generation. To achieve this goal, a sponge layer is used at the right-side end of the domain. By doing that, wave energy is damped and no waves are reflected towards the SG. Seven wave conditions listed in Table I have been used in combination with five different Wsg values (in total 35 cases). Figure 11 shows errors of wave height from theoretical values. As shown in the figure, most of the results show similar behaviour, within the error of 3 %. In general 3% of wave height difference is accepted in practice. From this result it can be concluded that generally the quality of wave generation is good and not so sensitive to Wsg value. Note that L/Wsg=1, 4 and 8 give slightly better results compared to other L/Wsg values. Figure 12 shows an example of the time series for Case 1 with L/Wsg=4. As can be seen, the result of SG are comparable to ones in the piston case ([5]) and to the theoretical case.

Ourense, Spain, June 13-15, 2017



Figure 11. Error of wave height with different wave properties and L/Wsg.



Figure 12. Theoretical and numerically obtained time series of water surface elevation (Case 1, L/Wsg=4)

## D. Applicability of SG in highly reflective condition with the default C function

The applicability of SG in a highly reflective conditions is tested in this section.

In case of perfect behaviour of the SG to absorb the reflected wave energy, a standing wave patter should be achieved, being the wave signal formed only by incident and reflected components of equal amplitude and in antiphase. Under this conditions, theoretically wave height at an anti-node point should become twice the incident wave height while no oscillation should be seen at a node point. To analyse the results, the measured wave height has been normalised by the theoretical one, assumed equal to twice the incident wave height. Figure 13 shows normalized wave height

distribution for reflected and re-reflected waves in Case 4 and 7. Those cases correspond to the best case (Case 7: wave heights for reflected and re-reflected waves are almost the same) and the worst case (Case 4: wave heights for reflected and re-reflected waves are most different) from all cases. Both cases have an antinode and a node point, which means that reflection is represented well. However, the magnitude of the normalized wave heights are different. In principle the normalized wave height should not change if reflected waves are not re-reflected at the SG. As long as there is no re-reflection at SG, no extra waves are introduced into the domain since all reflected waves are dissipated at the sponge layer part behind the SG. In Case 4, however, re-reflected wave is generated from the SG.

Figure 14 shows ratio of wave height (reflected waves) to wave height (re-reflected waves) for different wave properties and L/Wsg. The magnitude of the ratio is dependent on the case (different wave properties) and Wsg. The average ratio is 1.25 and therefore in general SG is feeding extra wave energy due to re-reflection in the highly reflective condition.



Figure 13. Normalized wave height for reflected and re-reflected waves (Case 4 and 7, L/Wsg=4).



Figure 14. Ratio of wave height (reflected waves) to wave height (re-reflected waves) for different wave properties and L/Wsg.

#### E. Location of the re-reflection

In this section, the location of the re-reflection is investigated in order to understand further the mechanism of the SG. To this end, two hypothesis are made: the first one is that the re-reflection is occurred at the offshore edge of the SG, and the second one is that the re-reflection is occurred at the center line of the SG.

In principle, the wave height ratio  $(H_Re-re/H_Re)$  is amplified when the distance between the re-reflection point and the wall becomes n times L/2 due to the resonance in the flume. Equation (3) represents the non-dimensional distance when the rereflection is occurred at the offshore edge of the SG, while Equation (4) represents the non-dimensional distance when the rereflection is occurred at the center line of the SG. Figure 15 and Figure 16 show the ratio of wave height (reflected waves) to wave height (re-reflected waves) for different wave properties and L/Wsg for each case. In Figure 15, the wave height ratio is amplified as it comes closer to the value of 0.25. On the other hand, in Figure 15, there is no clear trend. From those results, it is a clear that the re-reflection is occurred at the offshore edge of the SG.

$${l'}_{L} = \left| \frac{l' - \left(\frac{l'}{L/2}\right)\frac{L}{2}}{L} - \frac{1}{4} \right|, l' = distance from edge of Wsg to wall, L = wave length$$
(3)

$$\Delta^{l}/_{L} = \left| \frac{l - \left(\frac{l}{L/2}\right)\frac{L}{2}}{L} - \frac{1}{4} \right|, \qquad l = distance \ from \ center \ of \ Wsg \ to \ wall$$
(4)



Figure 15. Ratio of wave height (reflected waves) to wave height (re-reflected waves) for different wave properties and L/Wsg under an assumption that re-reflection is occurred at the offshore edge of the SG.



Figure 16. Ratio of wave height (reflected waves) to wave height (re-reflected waves) for different wave properties and L/Wsg under an assumption that re-reflection is occurred at the center of the SG.

## F. Summary of the SG method in a highly reflective condition

SG method has been tested in a highly reflective conditions with different wave properties and source generation size, in total 35 cases. It can be concluded that the SG method can generate enough accurate waves since most of the cases with sponge layer at the end of the domain show same wave height as the input value: mostly the error of wave height is within 3%. However, rereflection is occurred under the highly reflective condition (i.e. without sponge layer at the end of the domain). The location of the re-reflection is detected by sorting the result focusing on the resonance. It indicates that the re-reflection is occurred at the offshore edge of the SG.

#### V. APPLICABILITY OF SG-SWASH METHOD IN A HIGHLY REFLECTIVE CONDITION

#### A. SG-SWASH

One of the interests for practical applications in coastal engineering is how the SG method works for coupling, especially with SWASH. As described earlier, the particle velocity in the SG is controlled by analytical solution with a weighting function *C*, in principle. However, for the coupling, SWASH output can be used in the SG, instead of the analytical solution (hereafter this method is called as SG-SWASH). In this case, the velocities in the source generation are expressed as follows:

$$u_i = Cu_{si} + (1-C)u_{pi}$$
 (5)

$$\mathbf{w}_{i} = \mathbf{C}\mathbf{w}_{si} + (1 - \mathbf{C})\mathbf{w}_{pi} \tag{6}$$

where  $u_i$  and  $w_i$  are the controlled horizontal and vertical velocity,  $u_{si}$  and  $w_{si}$  are the horizontal and vertical velocity calculated from SWASH,  $u_{pi}$  and  $w_{pi}$  are the actual horizontal and vertical velocity calculated in DualSPHysics. Note that the control of the vertical component can be switched off, in that case  $w_{si}=w_{pi}$ .

#### B. Model Setup

One value for each parameter has been selected to apply for the numerical test cases in the Section V. The values are summarized as below. Slightly different values are used compared to the cases in the Section IV. However, the influence is quite limited since the error of the wave height (%) is almost zero for all the selected values as reported in the Section III.

- coefdt: 0 (not used)
- coefh: 1.9
- coefsound: 10
- dp/H: 1/15
- CFL: 0.2

Apart from the wave propagation parameter settings, the width of the source generation is set as L/Wsg=1. The value is again different from one used in the Section IV (L/Wsg=4) but the influence is limited as shown in Figure 11.

## *C.* Applicability of SG-SWASH in highly reflective condition with the default C function

Two extreme cases shown in Section IV, namely Case 4 and Case 7 are tested to investigate SG-SWASH. Figure 17 shows normalized wave height for reflected and re-reflected waves (Case 4 and 7, SG-SWASH). As can be seen in the figure, Case 4 gives

reasonable results while Case 7 has re-reflection. Note that 3 layers were used for the SWASH calculations and the control of the vertical component is switched off.

#### D. Arbitrary C function

The existing C function defined in Ni and Feng [8] gives certain amount of re-reflection from the SG as shown in Figure 14. This might due to the shape of the C function. In order to investigate the influence of the shape of C function, an arbitrary C function is defined below.

$$C = \frac{\left\{ \tanh\left(\left(\frac{2x}{Wsg} + \alpha\right)\beta\right) - \tanh\left(\left(\frac{2x}{Wsg} - \alpha\right)\beta\right)\right\} - \left\{\tanh\left((1 + \alpha)\beta\right) - \tanh\left((1 - \alpha)\beta\right)\right\}}{\left\{\tanh(\alpha\beta) - \tanh(-\alpha\beta)\right\} - \left\{\tanh\left((1 + \alpha)\beta\right) - \tanh\left((1 - \alpha)\beta\right)\right\}}$$
(7)

By changing  $\alpha$  and  $\beta$  in the equation, the shape of the C function can be changed arbitrary. The existing C function defined by Ni & Feng [8] is represented by  $\alpha$ =0.5 and  $\beta$ =2.5.

Figure 18 shows a newly defined C function ( $\alpha$ =0.1,  $\beta$ =5) compared to the existing C function. Note that the newly defined C function is an optimized set of values from a sensitivity analysis.



Figure 17. Normalized wave height for reflected and re-reflected waves (Case 4 and 7, L/Wsg=1, SG-SWASH).



Figure 18. A newly defined C function comared to the existing C function

#### E. Wave generation

Wave generation is tested with the optimized C function ( $\alpha$  =0.1,  $\beta$ =5) for the two extreme cases Case 4 and Case 7. Figure

19 and Figure 20 show time series of SG-SWASH and SWASH water surface elevations. As can be seen in the figures, both cases show good agreements of the time series. Note that 5 layers are used for the SWASH calculations and the control of the vertical component is switched on.



Figure 19. Theoretical and numerically obtained time series of water surface elevation (Case 4, L/Wsg=1, optimized  $\alpha$  and  $\beta$ ) in SG-SWASH case



Figure 20. Theoretical and numerically obtained time series of water surface elevation (Case 7, L/Wsg=1, optimized  $\alpha$  and  $\beta$ ) in SG-SWASH case

#### F. Applicability of SG-SWASH in highly reflective condition with the optimized C function

Those cases are also applied to the highly reflective condition. Figure 21 shows normalized wave height for reflected and rereflected waves (Case 4 and 7, optimized  $\alpha$  and  $\beta$ , SG-SWASH). As can be seen in the figure, both results give reasonable wave heights.

#### G. Summary of the SG-SWASH method

SG-SWASH method has been tested in a highly reflective condition with two wave conditions. By applying an optimized C function, SG-SWASH method gives good results not only for the wave generation case but also for the highly reflective condition case.



Figure 21. Normalized wave height for reflected and re-reflected waves (Case 4 and 7, L/Wsg=1, SG-SWASH with newly defined C function).

#### VI. CONCLUSIONS

SG and SG-SWASH methods have been implemented in DualSPHysics, and the applicability of those methods have been tested in a highly reflective condition.

In general, both models are capable to generate target waves with a good accuracy. On the other hand, re-reflection is occurred at the wave generation zone under the highly reflective condition in the most of the tested cases if existing C function is used. This problem is solved by introducing new C function with an optimized values for  $\alpha$  and  $\beta$ .

#### ACKNOWLEDGEMENT

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#### REFERENCES

- J.L. Lara, N. Garcia, I.J. Losada, RANS modelling applied to random wave interaction with submerged permeable structures, 53 (2006) 395– 417. doi:10.1016/j.coastaleng.2005.11.003.
- [2] A.C. Crespo, J.M. Dominguez, A. Barreiro, D. Benedict, M. Go, GPUs, a New Tool of Acceleration in CFD: Efficiency and Reliability on Smoothed Particle Hydrodynamics Methods, 6 (2011). doi:10.1371/journal.pone.0020685.
- [3] M. Narayanaswamy, A. Jacobo, C. Crespo, R.A. Dalrymple, SPHysics-FUNWAVE hybrid model for coastal wave propagation SPHysics-FUNWAVE hybrid model for coastal wave propagation Modèle hybride SPHysics-FUNWAVE pour la propagation côtière des vagues, 1686 (2017). doi:10.3826/jhr.2010.0007.
- [4] C. Altomare, J.M. Domínguez, a J.C. Crespo, T. Suzuki, I. Caceres, M. Gómez-Gesteira, Hybridization of the Wave Propagation Model SWASH and the Meshfree Particle Method SPH for Real Coastal Applications, Coast. Eng. J. 57 (2015) 1550024. doi:doi:10.1142/S0578563415500242.
- [5] Altomare, C; Domínguez, J M; Barreiro, A.; Crespo, A. J. C.; Suzuki, T; Gómez-Gesteira, Numerical wave dynamics using Lagrangian approach : wave generation and passive & active wave absorption, in: SPHeric Conf., 2015.

https://drive.google.com/open?id=0ByoalPrGoNQveDN4RlpBNENIeGM

- [6] C. Altomare, T. Suzuki, X. Chen, T. Verwaest, A. Kortenhaus, Wave overtopping of sea dikes with very shallow foreshores, Coast. Eng. 116 (2016) 236–257. doi:10.1016/j.coastaleng.2016.07.002.
- [7] T. Suzuki, C. Altomare, W. Veale, T. Verwaest, K. Trouw, P. Troch, M. Zijlema, Efficient and robust wave overtopping estimation for

impermeable coastal structures in shallow foreshores using SWASH, Coast. Eng. 122 (2017) 108–123. doi:10.1016/j.coastaleng.2017.01.009.

- [8] X. Ni, W.B. Feng, Numerical Simulation of Wave Overtopping Based on DualSPHysics Xingye Ni 1, 408 (2013) 1463–1471. doi:10.4028/www.scientific.net/AMM.405-408.1463.
- [9] M. Israeli, S.A. Orszag, Approximation of radiation boundary conditions, 135 (1981) 115–135.

## Appendix B: SWASH workshop 2016

Basic concept

SWASH and other wave models

Inputs





















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#### Model application examples

SWASH accounts for the following physical phenomena

- Wave propagation, frequency dispersion, shoaling, refraction and diffraction
- Nonlinear wave-wave interaction (incl surf beat and triads)
- Wave breaking
- Wave runup
- Wave interaction with structures

• etc Vlaanderer

#### **Relation to other models**

#### **Boussinesq model**

- Boussinesq model is a popular model for calculating wave propagation in a deep water. The accuracy is maintained by including the higher order terms in the equation.
- SWASH use number of layers to maintain the accuracy (frequency dispersion)
- Boussinesq models are in general using a lot of tricks to represent physical phenomena (wave breaking, moving shorelines, etc) whereas SWASH does not use any numerical filter.



#### Relation to other models Circulation & coastal flow models • SWASH is a non-hydrostatic wave-flow model and is originally designed for wave transformation in coastal waters. However, with the extension of meteorologinal and baroclinic forcing and solute transport, the model is capable

Comparable to WAQUA, Delft3D-FLOW, ADCIRC, ROMS,

of using for large scale flow and transport phenomena driven by tidal, wind and buoyancy forces.

FVCOM, UNTRIM, SLIM and SUNTANS.































Efficiency / Feasibi	) lity (e.g. indi H-DualSPHy	vidual overtopping rsics	g wave / force)	
Time: 0.0 s		ЅРН	GPU: GTX 590 Particles: 386,335 Runtime: 8.6 h	
CPU: Intel Xeon Grids: 200 Runtime: 7 s	SWASH	SPH	GPU: GTX 590 Particles: 118,321 Runtime: 3 h	











#### Final report

#### **Commands for model description**

CGRID: defines dimensions of computational grid [xpc] [ypc] [alpc] [xlenc] [ylenc] [mxc] [myc] 7.8 0.0 0.0 52.0 0.0 2600 0 [xpc] geographic location of the origin of the computational grid in the problem coordinate system (x-coordinate, in m). ... -> SWASH user manual (v 3.14.A) page 26

> 1. MODE NUMEST (MED). SET LEVEL 0.980+ 1. 1. 1. 0.0 0.0 52.0 0.0 2800 0+ 0.0 0.0 0+ 51 INFORID BOTTOM 0.0 0.0 0.0 5200 0 0.02 0.00 FEADINF BOTTOM 1. ONF\_134.bot 1 0 FREE+ BU SIDE W COW BTYPE WEAK CON SERIES 'OWF\_134.bvd's BOU SIDE E COW BTYPE NOIATION: SPON R1 NO.4

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#### **Commands for model description** VERT: defines vertical grid schematisation friction grids 1: One layer .. -> SWASH user manual (v 3.14.A) page 28 when kd value (2\*pi\*depth/wave length) is small (e.g. kd<0.5 gives wave celerity error 1%), one layer is fine. ... -> SWASH user manual (v 3.14.A) page 91 10WE 1241 OMAGEL INPUTIONIN \$1 MOTE NUNST ONED: \$1 9: 9: 9: 7.8 0.0 0.0 52.0 0.0 2800 0: \$1 INFGRID BOTTON 0.0 0.0 0.0 3210 0 0.02 0.00 READINF BOTTON -1. 00F\_134.bot 1 0 FREE+ Vlaanderer Vlaanderen Ð 1/2







#### **Commands for model description**

**BOU**ndcond: defines a boundary condition at the boundary SIDE: the boundary is one full side of the computational grid W: from West

CCW: The length along a SIDE is measured in clockwise or CounterClockWise direction

BTYPE: with this option the type of boundary condition is given

 $\langle \rangle$ 



#### **Commands for model description Commands for model description** SPON: sponge layer FRIC: bottom friction RI: right side of the domain MANN: Manning 10.0: 10.0 m wide 0.012: manning coefficient of 0.012 ... -> SWASH user manual (v 3.14.A) page 48 ... -> SWASH user manual (v 3.14.A) page 51 EOU SIDE E CON BTYPE RADIATION+ SPON RI 10.0+ RIC MWN 0.0124 NON-INDROSTATICA DISCRET UPR NON-BOTCAL SHIFTA TIMEL 0.1 0.54 Suprementations and the second I ..... "(2002) FILE 'VE 131 (6)' TSEC DIST BOTL WAIL OUTPUT 001000.000 0.05 SEC-TSECT WHEE 'VE 131 (6)' TSEC DIST BOTL WAIL OUTPUT 001000.000 0.05 SEC-LIATER WHEE 'VE 134 (16)' TSEC DIST BOTL WAIL OUTPUT 001000.000 0.05 SEC-LIATER WHEAD 'VE 134 (16)' TSEC DIST BOTL WAIL OUTPUT 001000.000 0.05 SEC-UNERUD 'UNERUD 'VE 134 (16)' TSEC DIST BOTL WAIL OUTPUT 001000.000 0.05 SEC-UNERUD 'UNERUD 'VE 134 (16)' TSEC DIST BOTL WAIL OUTPUT 001000.000 0.05 SEC-UNERUD 'UNERUD 'VE 134 (16)' TSEC DIST BOTL WAIL OUTPUT 001000.000 0.05 SEC-UNERUD 'UNERUD 'VE 134 (16)' TSEC DIST BOTL WAIL OUTPUT 001000.000 0.05 SEC-UNERUD 'UNERUD 'VE 134 (16)' TSEC DIST BOTL WAILD 'VE 134 (16)' TSEC DIST BOTL WAIL OUTPUT 001000.000 0.05 SEC-UNERUD 'UNERUD 'VE 134 (16)' TSEC DIST BOTL WAIL OUTPUT 001000.000 0.05 SEC-UNERUD 'UNERUD 'VE 134 (16)' TSEC DIST BOTL WAIL OUTPUT 001000.000 0.05 SEC-UNERUD 'VE 134 (16)' TSEC DIST BOTL WAIL OUTPUT 001000.000 0.05 SEC-UNERUD 'VE 134 (16)' TSEC DIST BOTL WAIL OUTPUT 001000.000 0.05 SEC-UNERUD 'VE 134 (16)' TSEC DIST BOTL WAIL OUTPUT 001000.000 0.05 SEC-UNERUD 'VE 134 (16)' TSEC DIST BOTL WAIL OUTPUT 001000.000 0.05 SEC-UNERUD 'VE 134 (16)' TSEC DIST BOTL WAIL OUTPUT 001000.000 0.05 SEC-UNERUD 'VE 134 (16)' TSEC DIST BOTL WAIL OUTPUT 001000.000 0.05 SEC-UNERUD 'VE 134 (16)' TSEC DIST BOTL WAIL OUTPUT 001000.000 0.05 SEC-UNERUD 'VE 134 (16)' TSEC DIST BOTL WAIL OUTPUT 001000.000 0.05 SEC-UNERUD 'VE 134 (16)' TSEC DIST BOTL WAIL OUTPUT 001000.000 0.05 SEC-UNERUD 'VE 134 (16)' TSEC DIST BOTL WAIL OUTPUT 001000.000 0.05 SEC-UNERUD 'VE 134 (16)' TSEC DIST BOTL WAIL OUTPUT 001000.000 0.05 SEC-UNERUD 'VE 134 (16)' TSEC DIST BOTL WAIL OUTPUT 001000.000 0.05 SEC-UNERUD 'VE 134 (16)' TSEC DIST BOTL WAIL OUTPUT 001000.000 (16)' TSEC DIST BOTL WAIL OUTPUT 001000.000 0.05 SEC-UNERUD 'VE 134 (16)' TSEC DIST BOTL WAIL OUTPUT 001000.000 0.05 SEC-UNERUD 'VE 134 (16)' TSEC DIST BOTL WAIL OUTPUT 001000.000 (16)' TSEC DIST BOTL WAIL OUTPUT 0010000.000 (16)' TSEC DIST BOTL WAIL OUTPUT OUTPU \$1 THERETE BOTTOM 0.0 0.0 0.0 5200 0 0.02 0.00+ ESADINE BOTTOM -1. ONE\_134.bot 10 FREE+ #1 BOU SIDE W COW BTYPE WEAK CON SERVIES 'OWF\_134.brd's BOU SIDE E COW BTYPE RADIATION: SPON R1 10.04 TEST 1 0; COMPUTE 010000.000 0.015 SEC 004050.000 STOP: Vlaanderer Vlaanderer 1/2 (je 15

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#### Commands for model description

#### DISCRET: discritization

η):

UPW: indicates the type of discretization for momentum equations MOM: indicates that momentum must be conserved everywhere.

## ... -> SWASH user manual (v 3.14.A) page 65





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## Appendix C: Efficiency and accuracy of DualSPHysics code

## Efficiency and accuracy of DualSPHysics code applied to structural design in coastal engineering: a case study from the Belgian coast

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#### ABSTRACT

Numerical modelling can represent a useful and complementary tool to physical model tests. Sophisticated tools are now at a formative stage and here we are actively developing the novel, flexible numerical technique Smoothed Particle Hydrodynamics (SPH). As a meshless and Lagrangian technique, SPH is ideally suited to fluid and solid mechanics with highly nonlinear deformation and is opening new avenues of activity in several areas, notably fluid-structure interaction, multi-phase flows and importantly, engineering application and design. SPH describes a fluid by replacing its continuum properties with locally smoothed quantities at discrete Lagrangian locations. Thus, the domain can be multiply-connected with no special treatment of the free surface, making it ideal for examining complicated flow situations in wave-structure interaction phenomena. The open-source DualSPHysics code ([1]) has been developed to use SPH for real engineering problems (e.g. [2]). This work shows the capabilities of several numerical improvements, lately introduced to increase numerical efficiency and accuracy of the code: 1) variable resolution or particle refinement in the areas of interest; 2) coupling with wave propagation models; 3) wave generation and active wave absorption systems that resemble the physical facilities. Data from physical model tests carried out at Ghent University, are here used for validation. The experimental campaign studied the response of a parapet wall located on the crest of a sea dike for Blankenberge Marina (Belgium) under extreme wave conditions.



Numerical results and computational times of all the proposed numerical approaches are compared and discussed in the present work, which finally demonstrates that DualSPHysics model can be proposed as a complementary tool to physical model experiments for the design of coastal defences.

#### REFERENCES

[1] A.J.C. Crespo, J.M. Domínguez, B.D. Rogers, M. Gómez-Gesteira, S. Longshaw, R. Canelas, R. Vacondio, A. Barreiro, O. García-Feal, "DualSPHysics: open-source parallel CFD solver on Smoothed Particle Hydrodynamics (SPH)", *Computer Physics Communications*, 187, pp. 204-216, 2015.

[2] C. Altomare, A.J.C. Crespo, B.D. Rogers, J.M. Domínguez, X. Gironella, M. Gómez-Gesteira, "Numerical modelling of armour block sea breakwater with Smoothed Particle Hydrodynamics", *Computers and Structures*, 130, pp. 34–45, 2014.

# Appendix D: Long-crested wave generation and absorption for SPH-based DualSPHysics model

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## Long-crested wave generation and absorption for SPH-based DualSPHysics model





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#### ARTICLE INFO

Keywords: Wave generation Wave absorption Meshfree methods DualSPHysics Smoothed Particle Hydrodynamics

#### ABSTRACT

The present work presents a fully comprehensive implementation of wave generation and active wave absorption for second-order long-crested monochromatic and random waves in a WCSPH-based (Weakly Compressible Smoothed Particle Hydrodynamics) model. The open-source code DualSPHysics is used for the scope. The numerical flume resembles a physical wave facility, so that, the moving boundaries mimic the action of a piston-type wavemaker. The second-order wave generation system, capable of generating both monochromatic (regular) and random (irregular) waves, is implemented jointly with passive and active wave absorption. A damping system is defined as solution for passive absorption and is used to prevent wave reflection from fixed boundaries in the numerical flume. The use of active wave absorption allows avoiding spurious reflection from the wavemaker. These implementations are validated with theoretical solutions and experimental results, in terms of water surface elevation, wave orbital velocities, wave forces and capacity for damping the re-reflection inside the fluid domain.

#### 1. Introduction

Numerical models can be considered, in general, as a representation of physical processes with the help of the computers. The use of numerical models in coastal engineering has become more and more popular over the last decades thanks to the enormous research and development that has been carried out, both in the description of the physics and in the optimization of the computational resources. Several models and numerical techniques have been developed, each one with its own hypotheses, schematizations, simplifications and assumptions.

Numerical models require proper validations against results from experimental campaigns, but once validated, they represent a cheaper and faster alternative to physical models. Besides, scale effects, typical of tests carried out in physical facilities, can be avoided. Finally, restrictions of physical models, mostly related to measurement systems, can be overcome in a numerical model, where all the quantities of interest (freesurface elevation, orbital velocity, wave pressure, run-up, overtopping, etc.) can be easily obtained. Numerical models might not replace totally the physical models, however, for the aforementioned reasons, they can be used for preliminary design of experimental campaigns and for the design of coastal defences in those cases where the limitations of the physical models cannot be completely overcome. Nowadays physical and numerical models are used together following a more general concept of composite modelling. Hence, numerical models need to be accurate, robust, sufficiently fast and versatile.

Different types of numerical models exist and are applied to coastal engineering; each of them presents its own capabilities and shortcomings when simulating a particular phenomenon. In particular, models based on Boussinesq equations, non-linear shallow water (NLSW) equations and Navier-Stokes (NS) equations are often used as wave propagation models for coastal engineering applications. Boussinesq equations models (e.g.: Peregrine, 1967; Madsen and Sørensen, 1992; Nwogu, 1993) are depth integrated models which retain non-linearity and dispersion of the waves. The NLSW equations are a simplified form of the Navier-Stokes equations, assuming depth-integrated free-surface flows. Traditionally, the pressure is assumed hydrostatic in NLSW models, although new generation models, like SWASH (Zijlema et al., 2011) have the option to consider either hydrostatic or non-hydrostatic pressure.

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NLSW models are ideal to propagate long time series of waves along large domains with very limited computational costs (e.g.: Suzuki et al., 2017). Fully NS equation-based models usually require more computational resources, however the increase in computational powers and the use of resources like Graphic Processor Units (GPUs) has fostered the development of NS models and their application to real cases in engineering. NS models describe the flow in three dimensions, by solving for pressure, velocity and, usually, turbulence in time and space. Depending on how the NS equations are solved, these models can be classified as Eulerian or Lagrangian. The Eulerian models consider the fluid as a continuum discretised in control volumes. In Eulerian models, a special treatment of the free-surface motion is required, differently from Lagrangian models where the tracking of free surface is an intrinsic property of the fluid discretization in unit elements or particles. Some examples of NS models based on Eulerian approach in computational fluid dynamics are: CO-BRAS (Cornell Breaking Waves and Structure) based on the work of (Liu et al. (1999), VOFbreak<sup>2</sup> (Troch and De Rouck, 1999a), FLOW-3D (www. flow3d.com) and IHFOAM (Higuera et al., 2013) based on OpenFOAM (www.openfoam.com). NS models overcome the limited representations of Boussinesq and NLSW models as, for example, those related with wave breaking, vertical flow characterization and flow inside porous structures. Eulerian models are applicable to a wide range of coastal structures, both permeable and impermeable, with complex geometries such as rubble mound breakwaters, cantilever structures and recurve walls. Regular and random waves can be generated, with active absorption functionality. Nevertheless, these methods require expensive mesh generation and present severe technical challenges associated with implementing conservative multi-phase schemes which can capture the nonlinearities within rapidly changing geometries.

The other category of NS equation-based models consists of meshless models, where the wave field is generally specified through a Lagrangian approach. Within this category, Smoothed Particle Hydrodynamics method (SPH) has become very popular among researchers in coastal engineering over the last decade. In general, SPH methods applied to free-surface flows can be categorized into weakly compressible and incompressible methods. In weakly compressible SPH (WCSPH), the fluid pressure is obtained from the Tait's equation of state, (e.g.: Dalrymple and Rogers, 2006). Instead, the incompressible particle methods such as incompressible SPH (ISPH) methods solve a Poisson pressure equation (Khayyer et al., 2008; Gotoh et al., 2014; Gotoh and Khayyer, 2016; Skillen et al., 2013).

For free-surface flows simulations and wave-structure interaction analysis, SPH method generally presents some remarkable advantages in comparison with meshbased methods, such as: i) no special treatment to detect the free surface; ii) straightforward modelling of moving complex boundaries and interfaces; iii) no need of special variables to detect different phases in the space since each individual particle holds material properties of its phase; iv) natural incorporation of coefficient discontinuities and singular forces into the numerical scheme. The meshless nature of an SPH-based model allows catching the violent hydrodynamics of the sea waves that, break, run-up, overtop sea dikes or breakwaters, acting on coastal structures, buildings or elements of the urban furniture along the seafront. Therefore, the application of SPHbased models to study sea waves interacting with beaches and coastal defences has increased during the last few years (Heller et al., 2016; Rogers et al., 2010; Barreiro et al., 2013; Vanneste et al., 2014; Altomare et al., 2015; Shadloo et al., 2015; Liu et al., 2015a).

If numerical modelling is offered as alternative or as complementary tool to physical wave facilities, a detailed and accurate wave generation and absorption becomes mandatory. This concept, applied to an SPH model, is the main reason behind the present work. Hence, the aim is to implement a proper wave generation and absorption system in the DualSPHysics model. DualSPHysics has been recently applied to freesurface flow problems and it has been proven to give results in agreement with physical model and in-situ data (Altomare et al., 2015; Ren et al., 2014; St-germain et al., 2014; Altomare et al., 2014). Furthermore, the capability of DualSPHysics to cope with free-surface flows and moving boundaries has been recently highlighted in G.M. Crespo et al. (2017) where the first SPH simulation of a floating oscillating water column device moored to the seabed has been presented. However, the model applicability has been limited in most of the works mentioned above by the lack of a proper wave absorption and optimised wave generation system.

Wave generation is, in fact, a critical issue in any numerical and physical model employed for coastal engineering purposes. The seminal work of Havelock (1929) who developed a theory for forced waves in both infinite and finite water depth is here adopted. The first order solution to the wavemaker problem defined in Havelock (1929) for piston and hinged wavemakers was first given by Biesel and Suquet (1951) and afterwards improved by several authors, such as Ursell et al. (1960), Flick and Guza (1980) and Schäffer (1996). All these theories were applied in physical models and they are widely used nowadays.

A comprehensive review on the mechanisms to simulate waves in numerical models is presented in Higuera et al. (2015). The authors define three main types of wave generation: internal, static-boundary and moving boundary wave generation. Examples of internal wave generation exist for RANS (Lin and Liu, 1999) and potential flow models (Schäffer and Sørensen, 2006). In SPH, Liu et al. (2015b) proposed a nonreflective internal wavemaker algorithm, where a momentum source term derived from the Boussinesq equations is employed and added into the Lagrangian form of Navier-Stokes equations for an Incompressible SPH model. The second mechanism corresponds to static wave generation and absorption (i.e. Dirichlet-type boundary conditions). Examples include RANS (Higuera et al., 2013; Troch and De Rouck, 1999b), NLSW models (e.g. SWASH: Zijlema et al., 2011) and potential flow models (Wei and Kirby, 1995). The third mechanism mimics the wave generation as in experimental facilities, implementing a moving boundary as a numerical wavemaker that generates and absorbs waves. Despite the difficulties to be applied to Eulerian models, since it involves mesh deformation, examples can be found in Higuera et al. (2015), Lara et al. (2010) and Vanneste and Troch (2012). This third type of wave generation is an ideal candidate to be implemented in SPH models because of their Lagrangian nature, so that a moving boundary is used. Examples can be found in Didier and Neves (2012), Manenti et al. (2008) and Meringolo et al. (2015).

Nevertheless, and despite much of literature on the application of SPH to coastal engineering problems, a fully detailed implementation of the wave generation and wave absorption systems for monochromatic and random waves in SPH is missing.

Manenti et al. (2008) and Meringolo et al. (2015) focused on cases where only monochromatic waves are generated without any active absorption system. Didier and Neves (2012) implemented wave generation and wave active absorption technique for a piston-type wavemaker in their SPH-based model (Gomez-Gesteira et al., 2012), being the wave absorption technique based on the work of Schaffer and Klopman (2000), similar to that presented in this work. However, they did not consider non-linear wave generation, and only regular waves were performed and validated. Ni and Feng (2013) presented a 2-D numerical wave tank based on an open-source SPH-based DualSPHysics model (Crespo et al., 2015), using a source generation and absorption technology with analytical relaxation approach. In this case, instead of moving boundaries, the water particles within the generation zone move following periodical velocities according to Stokes wave theory. This approach was applied and validated only for regular wave cases. Neither irregular waves nor second-order bound long waves were considered. Furthermore, this kind of generation has a higher computational cost than wave generation based on moving boundaries, due to the larger number of water particles needed in the generation zone and in the sponge layers (Ni et al., 2014). Wen et al. (2016) implemented an absorbing wavemaker in SPHysics model (Gomez-Gesteira et al., 2012). However, wave generation was only based on linear wave theory and the presented results only focused on regular wave tests. Omidvar et al. (2013) used an

irregular wave generation based on the linear wave theory to generate focused waves. Nor super-neither sub-harmonic components were considered in their approach. Other authors, (e.g.: Lo and Shao, 2002; Liu et al., 2016; Sampath et al., 2016; Wei et al., 2015), implemented wave generation techniques for solitary waves only.

Besides wave generation, wave absorption is also a key issue in any physical or numerical model applied to coastal engineering. Passive wave absorbers could be required to damp the wave energy and to reduce reflection exerted by the boundary of the model domain. Passive wave absorption systems traditionally consist of placing a gentle slope, porous material or screens in front of the boundaries to dissipate a large amount of the incident wave energy. They are usually designed for specific wave conditions. An algorithm that introduces a damping region in the fluid domain is implemented in DualSPHysics. The principle is similar to the use of a sponge area or porous material in the physical model tests.

Passive absorption is not enough if sea waves interacting with coastal or offshore structures are studied. Active wave absorption system is then needed. In active absorption, the wavemaker acts as a moving boundary whose movement is corrected to cancel out the reflected waves and to damp the re-reflection phenomenon. The control signal that is used to modify the wavemaker displacement in time is obtained through a transformation of the wave signal, to which an appropriate time-domain or frequency-domain filter is applied. The different types of active wave absorption systems depend on the hydrodynamic feedback that is used as correction signal for the wavemaker: free-surface elevation at the wavemaker (e.g.: Schaffer and Klopman, 2000), free-surface elevation and/or orbital velocities at a fixed position in the fluid domain (Frigaard and Christensen, 1994) and forces acting on the wavemaker (Salter, 1981). The active wave absorption system developed in this work is based on the theory described in Schaffer and Klopman (2000) that implements the free-surface elevation measured at the wavemaker.

The details of wave generation algorithms, passive and active absorption techniques are described in the present work for the specific case of DualSPHysics model. The new algorithms have been validated for different wave conditions.

The paper is structured as follows. A brief description of the SPH method and the DualSPHysics model is provided. Then, the theory for long-crested wave generation and absorption is presented. The model is validated with theoretical results in order to prove the performance of the implemented modules for wave generation and absorption. Then, a case of study is presented where the new implementation is validated with laboratory experimental data, overcoming the limitations of the work presented in Altomare et al. (2015). Finally, the main conclusions are presented.

#### 2. Smoothed Particle Hydrodynamics model

Smoothed Particle Hydrodynamics is a fully Lagrangian and meshless method (Violeau, 2012) where the fluid is discretised into a set of particles or nodal points. Physical quantities of each particle, such as position, velocity, density and pressure, are computed as an interpolation of the values of the neighbouring particles. The contribution of the nearest particles is computed depending on the distance between particles and using a weighted kernel function (*W*). The area of influence of the kernel function is defined using a characteristic length called smoothing length ( $h_{SPH}$ ). In addition, the kernel presents compact support to avoid contributions with other particles beyond that distance.

The DualSPHysics code (Crespo et al., 2015) is used in this work and the following governing equations have been implemented in the software.

#### 2.1. SPH formulation

The discrete SPH Lagrangian system of governing equations of weakly compressible flow, following Monaghan (1992), is

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$$\frac{d\rho_a}{dt} = \sum_b m_b (\mathbf{v}_a - \mathbf{v}_b) \, \nabla_a W_{ab} \tag{1}$$

$$\frac{d\mathbf{v}_{a}}{dt} = -\sum_{b} m_{b} \left( \frac{P_{b} + P_{a}}{\rho_{b} \cdot \rho_{a}} + \Pi_{ab} \right) \nabla_{a} W_{ab} + \mathbf{g}$$
<sup>(2)</sup>

$$\frac{d\mathbf{r}_a}{dt} = \mathbf{v}_a \tag{3}$$

being *t* time, **r** position, **v** velocity, *P* pressure,  $\rho$  density, *m* mass, **g**=(0,0,-9.81) m s<sup>-2</sup> the gravitational acceleration and  $W_{ab}$  the kernel function that depends on the distance between particles *a* and *b*. The Quintic kernel (Wendland, 1995), where the weighting function vanishes for inter-particle distances greater than  $2h_{SPH}$ , was adopted for the present study.  $\Pi_{ab}$  is the viscous term according to the artificial viscosity proposed in Monaghan (1992).

The system is closed by the addition of Tait's equation of state

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

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

More details about formulation can be found in Crespo et al. (2015) and more particular parameters that have been used in the simulations of this work can be found in Altomare et al. (2015).

#### 2.2. Boundaries

In the DualSPHysics code, boundaries are described using a discrete set of boundary particles that exert a repulsive force on the fluid particles when they approach the boundary particles. A dynamic boundary condition (Crespo et al., 2007) is used, where the boundary particles satisfy the same equations as the fluid particles, however they do not move according to the forces exerted on them. Instead, they remain fixed (fixed boundary) or move according to some externally imposed movement (moving boundary such as gates, flaps ...). Using this boundary condition, when a fluid particle approaches a boundary particle and the distance between them decreases beyond the kernel range, the density of the boundary particles increases giving rise to an increase in pressure. This results in a repulsive force being exerted on the fluid particle due to the pressure term in the momentum equation.

#### 3. Wave theory and implementation

#### 3.1. Wave generation

A second-order wave generation has been implemented in Dual-SPHysics model for piston-type wavemaker only, since this is considered more suitable than a flap-type wavemaker for intermediate and shallow water depths, which are the most usual conditions in coastal engineering applications. In addition, only long-crested waves are generated at this stage. Therefore, the numerical model aims to resemble a physical wave flume or a wave basin equipped with a long-crested wave generation and absorption systems. The wave generation theory used in the present work will be discussed in the following sections, starting from the linear theory for monochromatic waves and introducing then the modification from Madsen (1971) that represents an extension to second-order Stokes waves. Finally, the wave generation for irregular wave trains with assigned wave spectra will be discussed. A proper second-order wave generation is implemented for irregular waves to suppress spurious long waves. Therefore, the so-implemented wave generation technique represents an advance in SPH modelling towards a more complete representation of real sea states in comparison with previous works (Didier

and Neves, 2012; Manenti et al., 2008; Meringolo et al., 2015; Omidvar et al., 2013).

#### 3.1.1. First-order wave generation for monochromatic waves

The Biesel transfer functions express the relation between wave amplitude and wavemaker displacement (Biesel and Suquet, 1951), under the assumption of irrotational and incompressible fluid and constant pressure at the free surface. The far-field solution for the freesurface elevation can be expressed as follows

$$\eta(x,t) = \frac{H}{2} \cos(\omega t - kx + \delta)$$
(5)

where *H* is the wave height,  $\omega = 2\pi/T$  is the angular frequency,  $k = 2\pi/L$  is the wave number with *T* equal to the wave period and *L* the wavelength. The initial phase  $\delta$  is given by a random number between 0 and  $2\pi$ .

In general, only the far-field solution is interesting because the amplitude of a linear wave does not change with location. The near-field solution, which consists of a series of standing waves that decay in an exponential way from the wavemaker location, is neglected (Dean and Dalrymple, 1991).

The transfer function links the wavemaker displacement to the freesurface elevation, under the hypothesis of monochromatic sinusoidal waves. For a piston-type wavemaker the Biesel transfer function can be expressed as follows:

$$\frac{H}{S_0} = \frac{2 \cdot \sinh^2(kd)}{\sinh(kd) \cdot \cosh(kd) + kd}$$
(6)

where  $S_0$  is the piston stroke and *d* the water depth.

Once the piston stroke is defined, the time series of the piston movement is given by:

$$e_1(t) = \frac{S_0}{2}\sin(\omega t + \delta) \tag{7}$$

The work of Ursell et al. (1960) provided an experimental verification of the accuracy of the first-order wave generation theory for piston-type wavemakers. The authors carried out tests for waves of very small steepness,  $0.002 \le H/L \le 0.03$ , and higher steepness,  $0.045 \le H/L \le 0.048$ . The measured wave height was found to be on the average 3% below the predicted one for  $0.002 \le H/L \le 0.03$ . This error was comparable with experimental error. For higher steepness, the authors measured an error of 10% in average. Their work finally demonstrated that steep finite amplitude waves obtained using a first-order wave generation theory are smaller than the predicted ones.

## 3.1.2. Extension to the second-order wave generation theory (Madsen, 1971)

Attempts to generate regular waves in wave flumes using a solution based on the first-order wavemaker theory might produce unwanted spurious secondary waves that travel at a speed slightly lower than the primary waves. This causes a modification in wave profile and wave height (Goda, 1967). This unwanted secondary wave is generated due to the disagreement between the velocity that the wavemaker is forcing on the fluid, and the theoretical wave orbital velocities (Calabrese and Buccino, 2008). The modification to the primary waves becomes more severe as the wave steepness (H/L) increases and/or the relative water depth (d/L) decreases. Goda (1967) states that unwanted secondary waves will be generated when the ratio between the water depth and the wave length is lower than 0.15. This is a quite typical case for facilities equipped with a piston-type wavemaker. The implementation of a second-order wavemaker theory is therefore necessary to prevent the generation of spurious secondary waves. Fontanet (1961) was the first to give a complete solution to the second-order wavemaker problem. Madsen (1971) derived an approximate solution (d/L < O(0.1)),

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providing an explicit expression of the wavemaker motion required to eliminate the secondary waves, however his solution is valid only within certain ranges. More recently, Schäffer (1996) gave the complete second order solution to the wavemaker problem including super-harmonics and sub-harmonics for a piston- and a flap-type wavemaker. Goring (1979) developed a wavemaker theory based on cnoidal wave theory using a piston-type wavemaker. Schäffer and Steenber (2003) present a secondorder wavemaker theory for multidirectional waves. Zhang et al. (2006) developed a wavemaker theory based on stream wave theory.

The second-order wave generation theory implemented in Dual-SPHysics is based on (Madsen, 1971) who developed a simple second-order wave maker theory to generate relatively long second-order Stokes waves that would not change shape as they propagate. The theory proposed by Madsen (1971) is simple, controllable and affordable computationally. It proves to be accurate and quite efficient for waves of first and second order. An alternative solution is proposed in Hughes (1993) to suppress the secondary free waves. This solution was posed by Flick and Guza (1980) and consists in generating small amplitude waves in deep waters and then letting the wave shoal to shallow water in the wave tank. These authors notice that, in fact, the secondary waves become less important when shoaling occurs since the Stokes second-order wave grows faster than the secondary wave in such conditions.

Madsen's theory (1971) is finally implemented as described in Hughes (1993). The piston stroke  $S_0$  can be redefined from Eq. (6) as  $S_0 = H/m_1$  where:

$$m_1 = \frac{2 \cdot \sinh^2(kd)}{\sinh(kd) \cdot \cosh(kd) + kd}$$
(8)

Following Madsen (1971), to generate at 2nd order, an extra term should be added to Eq. (7). Therefore, the piston displacement for regular waves can be expressed as follows:

$$e(t) = \frac{S_0}{2}\sin(\omega t + \delta) + \left[\left(\frac{H^2}{32d}\right) \cdot \left(\frac{3\cosh(kd)}{\sinh^3(kd)}\right) - \frac{2}{m_1}\right]\sin(2\omega t + 2\delta)$$
(9)

where the second part of the right-hand term represents the second-order term. Madsen limited the application of Eq. (9) to waves that complied with the condition given by  $HL^2/d^3 < 8\pi^2/3$ , where the left-hand term defines the Ursell number. From a practical point of view, a specific warning is implemented in DualSPHysics to inform the user whether or not this condition is fulfilled.

## 3.1.3. Wave generation of irregular wave train with assigned wave energy wave spectra

Monochromatic waves are not representative of sea states that characterise real wave storm conditions. Sea waves are mostly random or irregular in nature. Irregular waves are generated in DualSPHysics using second-order wave generation theory that aims to compensate spurious long waves in order to generate properly both short waves and bound long waves.

Initially, the method described in Liu and Frigaard (2001) was used in DualSPHysics to generate random waves by implementing a first-order wave generation algorithm: the irregular wave train is generated by combining the discrete amplitude wave spectrum corresponding to the target wave energy spectrum with random phases obtained by a random number generator. Details on the method of Liu and Frigaard (2001) as implemented in DualSPHysics are omitted for the sake of simplicity and can be found in the DualSPHysics user guide (Team, 2016).

In DualSPHysics, two standard wave spectra have been implemented and used to generate irregular waves: JONSWAP spectrum and Pierson-Moskowitz spectrum. The characteristic parameters of each spectrum can be assigned by the user together with the value of N (number of wave components in which the spectrum is divided). DualSPHysics allows the user to choose among four different ways to define the bandwidth  $\Delta f$ :

uniformly distributed bandwidth (equidistant splitting of the wave spectrum, Fig. 1a), unevenly distributed bandwidth (Fig. 1b), cosine stretched function (Fig. 1c) and stretched algorithm (Fig. 1d).

Using a uniformly distributed bandwidth, the angular frequency can be determined assuming an equidistant splitting,  $f_i = f_{i-1} + i\Delta f \cdot \Delta f/2$ .

With unevenly distributed bandwidth, the angular frequency is chosen randomly as follows: the spectrum is divided in N intervals with bandwidth randomly selected between  $0 \cdot \Delta f$  and  $2 \cdot \Delta f$  and the angular frequency  $f_i$  is selected as the middle value of each interval. An unevenly distributed bandwidth should be preferred at least to the uniform bandwidth. In fact, depending on N, an equidistant splitting can lead to the repetition of the same wave group in the time series, fact that can be easily avoided using an unevenly distributed bandwidth. If there is a certain wave group that is being repeated, the full range of wave heights and wave periods is not reproduced and the irregular wave train is not statistically representing a real sea state of random waves. The cosine stretched function is a different way to calculate all the spectrum components: the wave spectrum is discretised in components with denser fitting around the peak frequency and less dense on the tails of the spectrum by means of a particular function. By using the cosine stretched function, accurate results are attained in terms of wave height distribution and groupiness, even when the number of spectrum components, is relatively low, such as N < 200 (Niels Jacobsen, personal communications). Finally, the stretched algorithm divides the wave spectra in components of equal area (i.e. energy), with the limitation for the tails of the spectra where the band width of two adjacent components cannot differ more than  $2 \cdot \Delta f$ . The four options have been tested in DualSPHysics for different values of N and the results have been compared in terms of significant wave height, spectral period, maximum wave height, wave height exceedance probability and groupiness factor. The results confirm that the cosine stretched function and the stretched algorithm are as accurate as the uniformly and the unevenly distributed bandwidth in terms of wave height distribution and groupiness, however a different value of N has to be used for each case. In general the cosine stretched function and the stretched algorithm need a lower number of wave components N than the other two methods, which results in greater computational efficiency.

A phase seed is also used to obtain different time series of irregular waves assigning randomly a value for the initial phase,  $\delta_{i}$ , to each wave component. Changing the phase seed allows generating different irregular wave time series with the same significant wave height ( $H_{m0}$ ) and peak period ( $T_p$ ). The influence of the selected time series on coastal processes can be in fact significant: previous research (Williams et al., 2014; McCabe et al., 2011, 2013) has underlined the role of the generated time series on wave-structure interaction phenomena, such as wave run-up and overtopping. Thereby the possibility to vary the phase seed has been implemented since it is considered mandatory for wave modelling. In addition, it can be easily varied by the DualSPHysics user and it is also independent from the execution platform.

#### 3.1.4. Second-order bound long waves

Bound long waves (BLW) refer to the set-down of the water level that is generated by wave groups. The set-down means that the bound long waves have their trough in the region of the higher waves in the wave group. This set-down is caused by the radiation stress. To balance this force, the set-down has to appear within the series of higher waves, with consequent set-up during the smaller waves (Fig. 2). These long waves are defined as bound because they tend to travel with the same group celerity. Typical period for the bound long waves are between 30 s and several minutes. Implementing the correct behaviour of bound long waves is very important, e.g. for harbour since the harbour resonance affects the behaviour of floating objects or moored elements. Furthermore, during wave breaking, the bound long waves are released (this might influence wave run-up or overtopping on a typical coastal dike, especially in shallow water conditions).

When natural waves are reproduced in a laboratory or in a numerical model the wave generator is normally controlled by a first-order signal. The set-down (bound long waves) generates drift velocities directed landwards under the crests and seawards under the troughs (Ottesen-Hansen et al., 1980). However, at the wave generator, the desired



Fig. 1. Example of standard wave spectrum with different band distribution (N = 64): a) uniform; b) unevenly; c) cosine stretched function; d) stretched algorithm.

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Fig. 2. Time series of first and second-order waves with bound long wave (BLW) components for a bichromatic wave train.

second-order drift velocities are not reproduced by a normal first-order signal. There is no flow through the paddle, therefore the natural drift velocities are compensated by identical ones with opposite signs. The latter velocities create a progressive long wave that is not bound anymore but free. This phenomenon is called parasitic long waves and it results in an exaggeration of the long wave effects. Second-order wave generation is required in order to cancel out this parasitic long wave to achieve the drift velocities that characterise the set-down. Another long wave, called displacement long wave, is caused by finite wavemaker displacements away from the mean position. The correction of the first-order wave generation at the wave paddle must be capable of compensating both parasitic long waves and displacement long waves (Sand, 1982). The method implemented in DualSPHysics is based on the solution for the control signal of the wavemaker that is described in Barthel et al. (1983). The reader can also refer to Hughes (1993) for further details on the second-order correction and equations for BLW.

#### 3.2. Passive wave absorption

The use of wave absorption allows generating long time series of sea waves in relatively short domains with negligible wave reflection. The passive wave absorption consists of a damping system at the end of the domain that reduces the wave energy (i.e. wave height and period). This system can be either a dissipative beach or a damping area: in experimental facilities, the latter one usually consists of porous material or perforated screens. A damping area has also been implemented in DualSPHysics. Results have been compared with those from cases implementing a dissipative beach. Dissipative beaches are systems where most wave energy is dissipated through the process of wave breaking.

Although the use of a dissipative beach as passive absorber is straightforward and it does not require any further implementation in the model, it also presents some disadvantages. A beach should be quite gentle and long to allow the waves to dissipate their energy; a beach should also exert very little reflection, which occurs generally in case of spilling wave breaker type. Moreover, the efficiency of the beach depends on the wave periods that characterise the wave trains. The beach can reduce reflection of short waves up to 10% while reflection of long waves can be very high (40%). The use of damping areas represents therefore a useful alternative to the dissipative beach. Previous works on SPH implement a sponge absorption layer to simulate wave tanks. Omidvar et al. (2011, 2013) presented a 2-D and 3-D model with a Riemann solver formulation where the sponge layer was implemented by changing the order of the Riemann solver approximation. Liu et al. (2016) and Lind et al. (2012) also used relaxation zones to absorb the wave reflection by implementing an exponential scheme that reduced the velocity of the

fluid particles.

The implemented damping system consists in gradually reducing the velocity of the particles at each time step according to their location, but using quadratic decay rather than exponential. In this way, the velocity is modified following

$$\mathbf{v} = \mathbf{v}_0 f(x, dt) \tag{10}$$

where  $\mathbf{v}_0$  is the initial velocity of the particle *i*,  $\mathbf{v}$  is the final velocity and *f*(*x*,*dt*) is the reduction function defined as

$$f(x,dt) = 1 - dt \cdot \beta \cdot \left(\frac{x - x_0}{x_1 - x_0}\right)^2 \tag{11}$$

where *dt* is the duration of the last time step, *x* is position of the particles,  $x_0$  and  $x_1$  are the initial and final position of the damping zone, respectively. It is recommended to use one wavelength, *L*, as the length of the damping zone, as suggested in Lind et al. (2012). The coefficient  $\beta$  modifies the reduction function that is applied to the velocity. In this work, a value of  $\beta = 10$  is used in all the simulations. A combination of damping zone and dissipative beach is also possible in Dual-SPHysics model.

#### 3.3. Active wave absorption

The active wave absorption system implemented in DualSPHysics is based on the time-domain filtering technique that uses the free-surface elevation at the wavemaker position as feedback for the control of the wavemaker displacement. The general assumption is linear long-crested wave theory in shallow water (Schaffer and Klopman, 2000; Dean and Dalrymple, 1991). The target wavemaker position *e*(*t*) is corrected in real time in order to avoid reflection at the wavemaker. The position in real time of the wavemaker is obtained through the velocity correction of its motion. Therefore, it is necessary to estimate the free-surface elevation of the reflected waves,  $\eta_R$ , to be absorbed, by comparing the target incident free-surface elevation,  $\eta_I$ , with the measured one in front of the wavemaker,  $\eta_{SPH}$ . This is measured at  $4 \cdot h_{SPH}$  from the wavemaker. This distance is selected to ensure that fluid particles used to measure freesurface elevation are not neighbours of the boundaries of the piston. The value of  $4 \cdot h_{SPH}$  is suggested, however larger distances (i.e. 5–10· $h_{SPH}$ ) have been tested and proved to lead to very similar results in terms of active wave absorption performance.

The reflected free-surface elevation can be expressed as:

$$\eta_R(t) = \eta_I(t) - \eta_{SPH}(t) \tag{12}$$

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Fig. 3. Definition sketch of AWAS-η system

The wavemaker velocity has to be modified to match the velocity induced by the wave that will be absorbed. For a piston-type wavemaker, characterised by uniform horizontal velocity along the water depth, the wave absorption is performed using linear long wave theory (Didier and Neves, 2012; Schaffer and Klopman, 2000). The velocity correction to absorb the reflected waves,  $U_R$ , can be expressed as follows:

$$U_R(t) = \eta_R(t)\sqrt{g/d} \tag{13}$$

where  $\eta_R$  is, as mentioned before, the free-surface elevation of the reflected waves and *g* is the gravitational acceleration.

The corrected wavemaker velocity  $U_C$  is the subtraction of  $U_R$  from the theoretical or incident wave maker velocity  $U_I$ . This  $U_I$  is the derivative in time of the wavemaker displacement e(t). Here the implementation details are expressed for the regular wave case. The theoretical velocity at time t,  $U_I(t)$ , can be computed as:

$$U_I(t) = \omega \frac{S_0}{2} \cos(\omega t + \delta)$$
(14)

The free-surface elevation in front of the wavemaker is measured, the target incident free-surface elevation is calculated and therefore the velocity correction  $U_R$  is estimated. The corrected wavemaker velocity at the instant t + dt can be expressed as:

$$U_{C}(t+dt) = U_{I}(t) - U_{R}(t)$$
(15)

The wavemaker position at t + dt is then corrected using the following expression:

$$e(t+dt) = e(t) + (U_C(t+dt) + U_C(t))\frac{dt}{2}$$
(16)

A sketch of the active wave absorption system is depicted in Fig. 3. The free-surface elevation  $\eta_{SPH}$ , measured in the numerical model, is transferred to a "filter box" that uses the above described algorithm to convert this information in a velocity correction  $U_R$  that, together with the theoretical velocity  $U_I$ , is passed to the "servo box" system that controls the wavemaker movement. The final result is the corrected wavemaker displacement e(t + dt).

Small deviations of the mean water level from the zero can imply accumulations in time leading to a drift of the wavemaker from its initial position that will grow indefinitely. This phenomenon can be also exacerbated by the fact that the near-field solution in Eq. (5) is neglected when the target waves are calculated at the wavemaker position. Constraints on maximum strokes do not exist in numerical models, however a drift might cause a change in the mean water level that finally would bias the simulation. In order to prevent this drift, the wavemaker should be forced back to its zero position. This action needs to be slow and smooth enough to minimise the effect on the generation of short waves. Hence, a drift correction algorithm is implemented in the code. The algorithm checks when the 80% of the maximum forward or backward stroke is reached (80% was assumed as default value but it can be modified by the

rable	1
Wave	conditions

-	Wave #1	Wave #2	
Height $H$ or $H_{m0}$	0.15 m	0.10 m	
Period T or $T_p$	2.00 s	3.00 s	
Depth d	0.66 m	1.50 m	
Steepness s	0.033	0.010	
Wavelength $L$ or $L_p$	4.52 m	10.22 m	

user). If this happens the wave board is pushed/pulled slowly back, while continuing to generate the target waves, in such a way that its average position will finally correspond to its initial zero-position (i.e. at the beginning of the simulation). A smoothed transition, in form of a power function, is used to prevent abrupt changes in the wavemaker displacement. The cases shown in the following sections did not require a drift correction. Therefore, no further details are provided here for sake of clarity.

#### 4. Validation with theoretical results

The implementation of wave generation and wave absorption techniques in DualSPHysics is validated against theoretical solutions for different wave conditions, both for monochromatic and irregular waves. The wave height (denoted as *H* for monochromatic waves and as its spectral value  $H_{m0}$  for irregular waves), wave period (denoted as *T* for



Fig. 4. Wave conditions on Le Mehaute abacus (Le Mehaute, 1976).



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Fig. 5. Setup of the numerical tank.

Table 2 Measuring points

	Wave #1	Wave #2
Wave gauges (WG) Velocity gauge (VG) Domain length ( <i>LX</i> ) Test duration ( <i>t</i> <sub>max</sub> )	x = 6.0, 6.5, 7.1 m x = 6.5 m; z = 0.4 m 11 m 35 s	

monochromatic waves and as peak period  $T_p$  for irregular waves), water depth (d), wavelength (L or  $L_p$  respectively) and wave steepness (s = H/L) are reported in Table 1. The wave conditions have been chosen to be representative of Stokes' second order waves; Wave #1 with high steepness and Wave #2 with low steepness (as can be seen in Fig. 4). The two cases are characterized by similar relative water depth ( $d/gT^2$ ), equal to 0.165 and 0.167 respectively.

The wave generation, implemented in DualSPHysics as described in §3.1, has been used for regular and irregular waves comparing the numerical results with theoretical solutions of free-surface elevation and

orbital velocities. Fig. 5 shows the setup of the 2-D numerical tank where the left wall consists of a moving boundary that pushes the water to generate waves (wavemaker) and the right wall is a vertical wall. WG1, WG2, WG3 are the wave gauge locations where the numerical freesurface elevations is computed and VG is the location where numerical orbital velocities are analysed. These locations and the domain length (*LX*) vary for Wave #1 and Wave #2 as shown in Table 2. The three wave gauges are used for wave reflection analysis. Therefore, the wave gauge locations vary with the wavelength. Wave reflection analysis has been performed by means of the WaveLab software (v.3.66) of the Aalborg University (http://www.hydrosoft.civil.aau.dk/wavelab/). The Mansard and Funke method (1980), implemented in WaveLab, has been used to measure wave reflection.

#### 4.1. Wave generation

In order to check the wave generation in DualSPHysics, each case of study is first modelled using a longer tank than the initial *LX* values reported in Table 2. Using a value of *LX* as in Table 2, it is expected that the



Fig. 6. Comparison between theoretical and numerical water surface elevation for regular waves at x = 6.0 m, x = 6.5 m, x = 7.1 m (Wave #1).



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Fig. 7. Comparison between theoretical and numerical horizontal (upper panel) and vertical (lower panel) velocity with regular waves at x = 6.5 m, z = 0.4 m (Wave #1).



Fig. 8. Comparison between theoretical and numerical water surface elevation for irregular waves at x = 6.5 m (Wave #1).

wave reflection on both-sides of the tank (piston and the right-side vertical wall) appears after a few seconds, since the wavelength and the size of the domain are comparable ( $LX/L \approx 2$ ). The case of the longer wave tank guarantees that wave reflection from the right-side vertical wall can be avoided during the simulation. The wave tank for Wave #1 is extended from 11 m to 45.2 m and wave tank for Wave #2 from 26 m to 102.2 m (which means approximately ten times the wavelength, L, for each case). It should be also noticed that 35 s and 50 s have been simulated for Wave #1 and #2 respectively. These durations are selected to guarantee that reflected waves do not reach the measuring points (Table 2) when simulating the longer tanks. Thus, the free-surface elevation was measured at WG1, WG2 and WG3 and the results were compared with theoretical solutions. The orbital horizontal and vertical velocities were measured at VG. Figs. 6 and 7 show the free-surface elevation and orbital velocities for the regular wave case (Wave #1). The results from the 45.2 m long tank match the theoretical solution,

proving that the waves are properly generated and there is no reflection during the 35 s of the simulation. The accuracy of the results has also been quantified and it will be discussed in  $\S4.4$ .

Similar results are obtained for irregular waves. The time series of free-surface elevation for Wave #1 is depicted in Fig. 8.

#### 4.2. Passive wave absorption

Both passive wave absorption systems (dissipative beach and damping area) have been modelled in DualSPHysics. The numerical tank is defined to resemble the one shown in Fig. 5 (i.e., same water depth and same wave characteristics) with the difference that the vertical wall at the right end of the tank is replaced by a dissipative beach with a 1:10 slope for Wave #1 (1:11 slope for Wave #2) or a damping area with  $\beta = 10$ ,  $x_0 = 11$  m and  $x_1 = 15.5$  m in Eq. (11) for Wave #1 ( $\beta = 10$ ,  $x_0 = 26$  m and  $x_1 = 36.5$  m for Wave #2). The aim is to avoid reflection



Fig. 9. Comparison between theoretical and numerical water surface elevation using the damping area and a dissipative beach for regular waves at x = 6.5 m (Wave #1).

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Fig. 11. Comparison between theoretical and numerical water surface elevation using the damping area and a dissipative beach for irregular waves at x = 6.5 m (Wave #1).

without using a large domain as described in previous section. The results using the passive absorption techniques have been compared with theoretical results (Stokes second-order wave theory). The time series of the free-surface elevation, measured at x = 6.5 m (WG2), are depicted in Fig. 9 for Wave #1. A good agreement is observed between numerical results and the theoretical solution. Similar results are also observed for the comparison of orbital velocities, not shown here for sake of simplicity.

A snapshot taken at t = 18.0 s of the numerical simulation is shown in Fig. 10 where the long tank of 45.2 m and the cases with a domain size of only 11 m but with both passive absorption systems are shown. The colours of the particles in the figure correspond to horizontal velocity and it can be noticed how the same velocity patterns (and free-surface profiles) are observed at the same instant with the three systems. The results (Figs. 9 and 10) confirm the effectiveness of the both absorption systems for monochromatic Wave #1.

The performance of the passive absorption has been verified for irregular waves (Fig. 11). The free-surface elevation measured with DualSPHysics for the dissipative beach and damping area are compared with the theoretical solution at x = 6.5 m (WG2) for Wave #1. The use of both passive absorption system leads to results that match theoretical results.

The reflection coefficient (the ratio between the amplitude of the reflected wave and the amplitude of the incident wave) has been estimated in each case (Table 3). Overall the results show a low reflection exerted by both the damping area and the dissipative beach, with similar values of reflection coefficient for each wave test case. It is important to

notice that the performance of both passive absorbers can be tuned by modifying the length of the damping area or the slope of the dissipative beach.

Fig. 12 plots the time series of the incident and reflected free-surface elevation using the damping area for the irregular case of Wave #1. The results show how the total signal and the incident component are very similar and the reflected component is much smaller (according to Table 3, the reflection coefficient for this case is equal to 8.6%).

#### 4.3. Active wave absorption

#### 4.3.1. Regular waves

For the case of wave generation with active wave absorption for monochromatic waves, a standing wave is expected to be generated in the computational domain (Troch and De Rouck, 1999a). Fig. 13 shows the time series at antinode (x = 9.04 m, equal to L/2 from the right-side wall) and at node (x = 10.17 m, equal to L/4 from the right-side wall) for the horizontal and vertical components of the orbital velocity (at z = 0.40 m) and the free-surface elevation in the case of Wave #1. The results from the Stokes second-order solution are also plotted, assuming perfect reflection at the right-side wall. In this specific case, to study any possible resonance due to residual re-reflection, the numerical domain was extended from 11.0 m to 11.3 m, equal to 5 L/2. In fact, resonant modes occur in enclosed areas when the basin size is multiple of half the wave length. In case of inefficiency of the active wave absorption system, having a numerical domain multiple of L/2, the residual oscillation due to re-reflection would result amplified. If the active wave absorption

Table 3

Values of reflection coefficient in case of passive absorption system for regular and irregular waves.

	Wave #1		Wave #2		
	Regular	Irregular	Regular	Irregular	
BEACH DAMPING	11.4% 12.2%	8.5% 8.6%	8.4% 7.9%	5.7% 6.5%	

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Fig. 12. Time series of the numerical water surface elevation using the damping area for irregular waves (Wave #1); total signal, incident and reflected component.



Fig. 13. Time series at antinode (x = 9.04 m) and at node (x = 10.17 m) for water surface elevation, horizontal velocity and vertical velocity (Wave #1) in the case of an 11.3 m long domain.

system performs well, the wavemaker behaves somehow as "permeable wall" to the reflected wave energy and re-reflection is prevented. In such a case a perfect standing wave pattern is achieved, then the free-surface elevation at node should be equal to zero and at antinode twice the amplitude of the incident waves. As it can be noticed in Fig. 13, although a perfect pattern is not achieved, the amplitudes at node are very small (about 2 cm) as predicted by the second-order solution and the amplitudes at antinode are close to their maximum.

The standing wave pattern is depicted in Fig. 14. Snapshots of the free-surface elevation, velocity field and velocity vectors are shown at seven time instants within a time window equal to 1.5 times the wave period. From both Figs. 13 and 14 it is noticeable that a good agreement is achieved between the expected theoretical behaviour and the numerical results.

#### 4.3.2. Irregular waves

The results obtained using active wave absorption for the irregular wave cases are described in this section. Assessing the performance of the system is less evident by visual inspection of the time series (free-surface elevation and orbital velocities). Therefore, only the separation between incident and reflected waves can provide an estimation of the accuracy of the technique. Results are reported in Table 4 in terms of incident significant wave height,  $H_{m0}$ , and the spectral period,  $T_{m-1,0}$ , as calculated from the reflection analysis performed with Wavelab v.3.66. The peak period  $T_p$  is not reported, however, since the measurement points are not so shallow, the spectrum shape does not diverge significantly from the generated spectra and the relationship between peak period and spectral period is almost equal to  $T_{m-1,0} = T_p/1.1$ . The results from the case with long numerical tank (§4.1) are also reported for comparison.

It should be reminded that only 35 s and 50 s have been simulated out of the entire wave train, respectively for Wave #1 and Wave #2. The reflection analysis has been therefore limited to this time window. This fact explains why the measured wave characteristics might differ from the theoretical input values (e.g.  $H_{m0} = 0.15$  m,  $T_p = 2.0$  s, for Wave #1). Therefore, the measured wave height and period from the case with long numerical tank (no reflection) are assumed as reference values in order to

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Fig. 14. Snapshot of the water surface elevation, velocity field and velocity vectors for standing waves during 1.5T (Wave #1).

assess the performance of the active absorption system. In this way, according to Table 4, the reference values (LONG) will be the incident significant wave height  $H_{m0} = 0.14$  m and the spectral period  $T_{m-1,0} = 2.15$  s, for Wave #1 and  $H_{m0} = 0.08$  m,  $T_{m-1,0} = 2.90$  s, for Wave #2. The values of the incident waves when using active wave absorption (AWAS) are in agreement with the reference ones (LONG) which demonstrates that the reflected wave component is compensated by AWAS also in case of irregular waves.

#### 4.4. Assessment of the method

This section collects all results with Wave #1 and Wave #2 both for regular and irregular waves. The efficiency of each implementation for passive and active wave absorption will be discussed and presented in terms of computational runtime. The numerical error will be quantified using the Taylor diagrams (2001). The influence of the initial interparticle distance, dp, on the model accuracy will be also analysed. For all cases in the present paper, the empirical coefficient used in the viscous term of Eq. (2), has been selected in accordance with Altomare et al. (2015). In addition, according to De Padova et al. (2014), the smoothing length ratio,  $h_{SPH}/dp$ , should be equal or higher than 1.4 for cases of regular wave breaking on plane slope. In the present work a value of  $h_{SPH}/dp$  equal to 1.7 has been used. Experience suggests that values ranging from 2 to 2.5 reduce the wave decay for cases with larger numerical domains.

#### 4.4.1. Efficiency and accuracy

The statistical results when comparing numerical measurements with theoretical solutions are shown in order to analyse the model accuracy. Moreover, the computational runtime for each case is also reported. All simulations corresponding to the same wave were performed creating particles with the same initial interparticle distance dp which leads to different number of particles (np) depending on the size of the domain. All cases were executed on the GPU "GeForce GTX TITAN Black". The total number of particles and the computational runtimes are shown in Fig. 15 for the irregular cases (similar values can be found for the regular cases). A value of dp = 7 mm was chosen for Wave #1 and dp = 5 mm for Wave #2. There is a linear dependence between the number of particles and the computational runtime. Note that the order of difference observed between values for Wave #1 and #2 is due to the different domain size (LX). It can be also observed that, in terms of the passive absorption mechanisms, the option of the dissipative beach is slightly more efficient than using the damping area (4% faster for Wave #1 and 6% for Wave #2). However, this results can change for different extension of the damping area or different dissipative beach slopes.

The error of the numerical free-surface elevation computed for Wave #1 and #2 (LONG, DAMPING, BEACH) compared with the Stokes' second order theory is represented using Taylor diagrams (2001). Thus, Fig. 16 shows the comparison between numerical and theoretical freesurface elevation at the three wave gauges, which is quantified in terms of correlation coefficient, normalized centred root-mean-square

Table 4

Incident wave characteristics: case with long numerical tank (LON	G) versus cases with active wave absorption (AWAS).
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	Wave #1		Wave #2	
	$H_{m0}$	<i>T<sub>m-1,0</sub></i>	$H_{m0}$	T <sub>m-1,0</sub>
LONG AWAS	0.14 m 0.15 m	2.15 s 2.07 s	0.080 m 0.081 m	2.90 s 2.91 s

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Fig. 15. Computational runtime and number of particles involved in each simulation of irregular waves (left: Wave #1, right: Wave #2).



Fig. 16. Taylor Diagram with a statistical comparison of numerical water surface elevations for Wave #1 (left) and Wave #2 (right).

difference ( $RMS_n$ ) and normalized standard deviation ( $STD_n$ ). The three points are very close so they cannot be clearly differentiated in the figure. The correlation coefficient ranges between 0.97 and 0.99, the  $RMS_n$  is lower than 0.25 and the  $STD_n$  is always higher than 0.85. These values show the DualSPHysics accuracy to generate and propagate Stokes'waves of second order. Similar model performance has been obtained for WG1, WG3 and orbital velocities at VG for all numerical tests.

#### 4.4.2. Convergence study

The initial interparticle distance, *dp*, used for Wave #1 and Wave #2

#### Table 5

Characteristics and ru	intimes of 5 cases	with different	resolutions.
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Case	dp [m]	H/dp	d/dp	Np [10 <sup>3</sup> ]	Runtime [h]	$STD_n$
dp1	0.0500	3.0	13.2	3.8	0.06	0.80
dp <sub>2</sub>	0.0220	6.8	30	19.7	0.14	0.89
dp <sub>3</sub>	0.0150	10.0	44	42.5	0.30	0.89
dp4	0.0070	21.4	94.2	192.8	2.02	0.91
dp <sub>5</sub>	0.0022	68.2	300	1953.7	51.52	0.92



Fig. 17. Water surface elevation for different resolutions with Wave #1 (and dissipative beach) compared with the 2nd order Stokes theoretical solution.



Fig. 18. Numerical model setup of the Blankenberge Marina test cases with a parapet wall (Fig. 10 in Altomare et al., 2015).

has shown to give accurate results, as described in the previous section. However, a convergence study has been also carried out. The regular wave case of Wave #1 with a dissipative beach was simulated using five different resolutions, corresponding to five different values of dp, as reported in Table 5. The ratios H/dp and d/dp, the total number of fluid particles, Np, and the computational runtimes are also reported. The error of the numerical modelling was calculated in terms of normalized standard deviation of the free-surface elevation measured at x = 7.1 m (as computed in Fig. 16). The time series of free-surface elevation for each dp is also plotted in Fig. 17. With a very coarse resolution (H/dp = 3.0), results are clearly worse than those using finer resolutions. All cases presented in the paper used H/dp = 21.4 for Wave #1 and H/dp = 20 for Wave #2. Moving to even finer resolutions (H/dp = 68.2) does not improve substantially the model accuracy. In addition, finer spatial resolution implies a much higher computational cost (the runtime is approximately 25 times bigger). Therefore, a value of H/dp = 21.4 was considered adequate for the scope of the present work.

As a rule of thumb, H/dp should always be higher than 10 to achieve an accurate modelling at an affordable computational cost; users must pay attention also to the ratio d/dp, for which an integer value is recommended in order to limit possible inaccuracies on the initial still water level.

#### 5. Case of application

The active wave absorption system (AWAS) aims to represent the real cases from open sea since there is no physical boundary where the waves are generated and then re-reflected once the reflected waves travel back after interacting with dikes, breakwaters, etc ... Therefore, the use of active absorption systems is of great interest, for instance, when the forces exerted onto coastal structures are studied in a wave tank in order to compensate unphysical wave re-reflection. This section will show a case of application where AWAS is necessary for the problem under scope.

Data from physical model tests are used for numerical model validation. The tests were carried out at Ghent University, Department of Civil Engineering (Belgium). The experimental campaign studied the response of new coastal defences proposed for the marina of



Fig. 19. Movement of the piston with and without active wave absorption.



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Fig. 20. Comparison between numerical and experimental wave forces for the Blankenberge Marina test case with a parapet wall.

Blankenberge, in Belgium. The work of Altomare et al. (2015) already showed the validation of DualSPHysics with these experiments. The numerical results were compared with physical model test data in terms of free-surface elevation and wave forces. However, in Altomare et al. (2015), re-reflection compensation was not yet implemented in Dual-SPHysics, meanwhile an active wave absorption system was used in the physical model tests. The agreement between numerical and experimental results was limited to a few wave impacts during the first seconds of simulation, but differences were noticeable after a certain time, specifically when the wave re-reflection occurred in the numerical model. In the present work, instead, a numerical active wave absorption system is implemented in DualSPHysics, so that, the same validation is carried out again in order to achieve better agreement for longer time series which will imply that the numerical system absorbs the re-reflected waves as well as the physical system did.

The dimensions of the numerical domain are shown in Fig. 18. The significant wave height,  $H_{m0}$ , is equal to 0.101 m and the peak period  $T_p$  is 2.68 s, both quantities expressed in model scale. The water depth at the wave paddle is 0.639 m. The numerical flume has been built to resemble the physical one with interparticle distance dp of 0.01 m leading to 126,200 fluid particles.

Only the theoretical movement of the piston was known from the physical tests. This movement corresponds to the input time series of wavemaker displacement given to the wave generation system. The real displacement of the physical piston differs from the input time series, because, during the experiments, the piston used active absorption to compensate the wave re-reflection. However, the information on the real piston displacement was not available for the present work. Fig. 19 plots



Fig. 21. Snapshot of the reproduced waves and horizontal velocity field from generation until impact.

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Fig. 22. Snapshot of the reproduced waves and pressure field from generation until impact.

the time series of the theoretical piston movement and of the movement of the piston simulated with DualSPHysics that implements AWAS as described in §3.3. The theoretical piston movement was used in Altomare et al. (2015) and does not include any correction for re-reflection compensation. The piston displacement does not deviate from the theoretical one, during the first 25s. After that time, the first incoming wave, reflected from the parapet wall (marked in red in Fig. 18), reaches the piston again. The movement of the numerical piston starts to diverge from the theoretical one in order to compensate the reflected wave and to avoid re-reflection (e.g, the piston is initially moving backwards between t = 25 s and t = 40 s).

A proper test to evaluate the correct behaviour of the numerical active absorption is the comparison of wave forces exerted on the parapet wall. It is worth reminding that the experimental forces were obtained using the active wave absorption in the physical tank, however the experimental facility and the DualSPHysics model implement different techniques to compensate re-reflection.

Fig. 20 shows the times series of the experimental and numerical wave forces. The previous results from Altomare et al. (2015) are shown in Fig. 20 and correspond to the version of DualSPHysics without AWAS (solid red line). The results using the latest implementation of Dual-SPHysics with AWAS are also included in the figure (solid blue line). An initial agreement between numerical and experimental results was already presented in Altomare et al. (2015), however it was limited to the first 70 s of simulation (top panel in Fig. 20), since the lack of a numerical AWAS caused differences that became noticeable after that instant. As shown in Fig. 19, AWAS starts to work after 25 s to compensate the rereflected waves that are reaching the wave generator. This causes small differences between case with and case without AWAS during the first 70 s of simulation (top panel in Fig. 20), but these differences are negligible. In both cases, the numerical results match the experimental results. The improvements for using AWAS are actually manifest analysing the bottom panel of Fig. 20. In the case without absorption, there is a clear phase shift between experimental and numerical results, especially visible after t = 75 s. Besides, the total duration of each impact without AWAS is larger than the case with AWAS. As consequence, the impulse of each impact is bigger without AWAS than with AWAS and bigger than the experimental one. In fact, the energy is building up in the system without AWAS, because of lack of any compensation for the rereflected waves. All these inaccuracies are overcome when a proper absorption system is used.

One could notice differences between numerical and experimental results that are depicted in Fig. 20, even when an active wave absorption system is implemented. Possible explanations for these differences are: a) the non-repeatability of the physical model tests and b) the differences in the active absorption techniques between DualSPHysics and the experimental facility. The former one is a well-known phenomenon in physical model tests (e.g.: Peregrine, 2003; Bullock et al., 2007; Kisacik et al., 2012) that should be considered to properly judge the model accuracy in terms of wave forces. The latter one can cause loss of correspondence between numerical and physical results, because of the difference in simulated wave reflection. This was also concluded in Vanneste et al. (2014).

Due to the aforementioned reasons, a statistical analysis of wave impacts, focused on the exceedance probability distribution of the force peaks, would give useful information to assess the accuracy of the numerical model. However, less than 30 peak events (corresponding to all peaks above a threshold of 20 N/m) have been identified in the time window that was simulated for the present paper. The low number of events makes the statistical analysis unreliable. Here, the difference between numerical results and physical ones has been estimated as difference between each peak value. Considering only the maximum force, the numerical value is 4% smaller than the physical one. In average the difference is about 20%, value that can be considered acceptable as suggested by Altomare et al. (2015), Kisacik et al. (2012) and Vrijling and Van Gelder (1999). Therefore, the improvements attained using AWAS in DualSPHysics are clearly demonstrated with respect to cases where a wave absorption system was not yet implemented, despite the existing differences in the wave force time series between numerical and experimental results, that can be ascribed to the aforementioned sources of uncertainty.

Fig. 21 shows three different instants that cover one of the reproduced waves from its generation (t = 60.7 s) until the impact on the parapet wall (t = 73.25 s). The horizontal velocity field is also depicted in the figure. The same instants are depicted in Fig. 22, where the pressure field is represented. The use of sophisticated pressure filters (e.g.: Antuono et al., 2010) can lead to even more smooth pressure fields, however it was not used in the present case of study. Nevertheless, the observed noise in the pressure field is negligible.

Based on the presented analysis and considering advantages and limitations of the proposed modelling, it can be concluded that Dual-SPHysics is a promising and efficient tool for practical application in

coastal engineering. In any case, it is worth mentioning that, even though numerical modelling can represent a useful tool for a first analysis of wave-structure interaction, the composite physical and numerical modelling is always recommended for design purposes (see, for example, Allsop et al., 2016).

#### 6. Conclusions and future work

Wave generation and wave absorption techniques have been implemented in the DualSPHysics model. The comparison of the absorption systems, presented in this work, with theoretical and experimental results demonstrates the reliability of the implementation. Thanks to this reliability in modelling sea waves, DualSPHysics is gradually becoming an alternative or complementary tool to physical models.

The new functionalities of DualSPHysics to generate and absorb waves allows the study of new engineering problems. Generally speaking, the active absorption system aims to represent the real cases from open sea since there is no physical boundary where the waves are generated, meanwhile the passive absorption mimics a case where no structure is located on the opposite side to the wave generator. The latter case is useful to study offshore floating bodies, wave energy converters, etc. and the former case is preferable to study the interaction between sea waves and coastal defences.

Some differences are noticed when the model has been applied to study wave forces on a storm wall located on top of a sea dike. However, there are factors related to the experimental tests that must be considered to properly judge the numerical results (i.e. non-repeatability of the tests, re-reflection compensation system). Despite the differences between numerical and experimental results, the use of a proper active wave absorption system improves the capability of the model to mimic real wave facilities and to provide reliable results by avoiding unphysical energy build-up.

Finally, it is important never to lose sight of the fact that even the most sophisticated laboratory facilities can only be tools to help with the overall research programs (Ploeg and Funke, 1985). Laboratory generated sea states, even when they are able to include all the known physical parameters, such as wind, currents, temperature differences, etc., will never become replicas in miniature of the real ocean. This general concept can be certainly applied to numerical models as well.

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#### References

- Allsop, B., Bruce, N.W.H., De Rouck, T., Kortenhaus, J., Pullen, A., Schüttrumpf, T., Troch, H., van der Meer, P., Zannutigh, J.W., 2016. EurOtop Manual on Wave Overtopping of Sea.
- Altomare, C., Crespo, A.J.C., Rogers, B.D., Dominguez, J.M., Gironella, X., Gómez-Gesteira, M., 2014. Numerical modelling of armour block sea breakwater with smoothed particle hydrodynamics. Comput. Struct. 130, 34–45. http://dx.doi.org/ 10.1016/j.compstruc.2013.10.011.
- Altomare, C., Crespo, A.J.C., Domínguez, J.M., Gómez-Gesteira, M., Suzuki, T., Verwaest, T., 2015. Applicability of Smoothed Particle Hydrodynamics for estimation of sea wave impact on coastal structures. Coast. Eng. 96, 1–12. http://dx.doi.org/ 10.1016/j.coastaleng.2014.11.001.
- Antuono, M., Colagrossi, A., Marrone, S., Molteni, D., 2010. Free-surface flows solved by means of SPH schemes with numerical diffusive terms. Comput. Phys. Commun. 181, 532–549. http://dx.doi.org/10.1016/j.cpc.2009.11.002.

Coastal Engineering 127 (2017) 37-54

- Barreiro, A., Crespo, A.J.C., Domínguez, J.M., Gómez-Gesteira, M., 2013. Smoothed Particle Hydrodynamics for coastal engineering problems. Comput. Struct. 120, 96–106. http://dx.doi.org/10.1016/j.compstruc.2013.02.010.
- Barthel, F.C., Mansard, V., Sand, E.,P., Vis, S.E., 1983. Group bounded long waves in physical models. Ocean. Eng. 10, 261–294.Biesel, F., Suquet, F., 1951. Etude theorique d'un type d'appareil a la houle. La Houille
- Biesel, F., Suquet, F., 1951. Etude theorique d'un type d'appareil a la houle. La Houille Blanche 2, 157–160.
- Bullock, G.N., Obhrai, C., Peregrine, D.H., Bredmose, H., 2007. Violent breaking wave impacts. Part 1: results from large-scale regular wave tests on vertical and sloping walls. Coast. Eng. 54, 602–617. http://dx.doi.org/10.1016/ i.coastaleng.2006.12.002.
- Calabrese, M., Buccino, M., 2008. The generation of periodic shallow water waves in a flume: theory and measurements. In: Proc. 2nd Int. Conf. on the Application of Physical Modelling to Port and Coastal Protection (Coastlab), Italy, Bari. ISBN: 9788860930460.
- Crespo, A.J.C., Gómez-Gesteira, M., Dalrymple, R., 2007. Boundary conditions generated by dynamic particles in SPH methods. Comput. Mater. Contin. 5, 173–184, 3478400 citeulike-article-id:
- Crespo, A.J.C., Domínguez, J.M., Rogers, B.D., Gómez-Gesteira, M., Longshaw, S., Canelas, R., Vacondio, R., Barreiro, A., García-Feal, O., 2015. DualSPHysics: opensource parallel CFD solver based on smoothed particle hydrodynamics (SPH). Comput. Phys. Commun. 187, 204–216. http://dx.doi.org/10.1016/ j.cpc.2014.10.004.
- Dalrymple, R.A., Rogers, B.D., 2006. Numerical modeling of water waves with the SPH method. Coast. Eng. 53, 141–147. http://dx.doi.org/10.1016/ j.coastaleng.2005.10.004.
- De Padova, D., Dalrymple, R.A., Mossa, M., 2014. Analysis of the artificial viscosity in the smoothed particle hydrodynamics modelling of regular waves. J. Hydraul. Res. 1686, 1–13. http://dx.doi.org/10.1080/00221686.2014.932853.
- Dean, R.G., Dalrymple, R.A., 1991. Wavemaker theory. In: Water Wave Mech. Eng. Sci. WORLD SCIENTIFIC, pp. 170–186. http://dx.doi.org/10.1142/9789812385512\_ 0006.
- Didier, E., Neves, M.G., 2012. A semi-infinite numerical wave flume using
- SmoothedParticle hydrodynamics. Int. J. Offshore Polar Eng. IJOPE 22, 193–199. Flick, R.T., Guza, R.E., 1980. Paddle generated waves in laboratory channels. J. Waterw.
- Port, Coast and Ocean Div. Am. Soc. of Civ. Eng. 106 (WW1), 79–97. Fontanet, P., 1961. Théorie de la génération de la houle cylindrique par un batteur plan,
- La Houille Blanche. P. Frigaard, M. Christensen, An absorbing wave-maker based on digital filters, in: Proc.
- 24th Int. Conf. Coast. Eng., 1994: pp. 168–180. doi:10.1061/9780784400890.014.
   G.M. Crespo, A.J.C., Altomare, Corrado, Domínguez, J.M., González-Cao, Jose, 2017. Towards simulating floating offshore oscillating water column converters with
- smoothed particle hydrodynamics. Coast. Eng. in Press. http://dx.doi.org/10.1016/ j.coastaleng.2017.05.001.Goda, Y., 1967. Travelling Secondary Wave Crests in Wave Channels.
- Gomez-Gesteira, M., Rogers, B.D., Crespo, A.J.C., Dalrymple, R.A., Narayanaswamy, M.,
- Dominguez, J.M., 2012. SPHysics development of a free-surface fluid solver Part 1: theory and formulations. Comput. Geosci. 48, 289–299. http://dx.doi.org/ 10.1016/j.cageo.2012.02.029.
- Goring, D.G., 1979. Tsunamis the Propagation of Long Waves onto a Shelf. California Institute of Technology.
- Gotoh, H., Khayyer, A., 2016. Current achievements and future perspectives for projection-based particle methods with applications in ocean engineering. J. Ocean. Eng. Mar. Energy 1–28. http://dx.doi.org/10.1007/s40722-016-0049-3.
- Gotoh, H., Khayyer, A., Ikari, H., Arikawa, T., Shimosako, K., 2014. On enhancement of Incompressible SPH method for simulation of violent sloshing flows. Appl. Ocean. Res. 46, 104–115. http://dx.doi.org/10.1016/j.apor.2014.02.005.
- Havelock, T.H., 1929. Havelock forces surface wave on water 1929. Philos. Mag. Ser. 7 (8), 569–576.
- Heller, V., Bruggemann, M., Spinneken, J., Rogers, B.D., 2016. Composite modelling of subaerial landslide–tsunamis in different water body geometries and novel insight into slide and wave kinematics. Coast. Eng. 109, 20–41. http://dx.doi.org/10.1016/ j.coastaleng.2015.12.004.
- Higuera, P., Lara, J.L., Losada, I.J., 2013. Realistic wave generation and active wave absorption for Navier-Stokes models. Application to OpenFOAM®. Coast. Eng. 71, 102–118. http://dx.doi.org/10.1016/j.coastaleng.2012.07.002.
- Higuera, P., Losada, I.J., Lara, J.L., 2015. Three-dimensional numerical wave generation with moving boundaries. Coast. Eng. 101, 35–47. http://dx.doi.org/10.1016/ j.coastaleng.2015.04.003.
- Hughes, S.A., 1993. Laboratory wave reflection analysis using co-located gages. Coast. Eng. 20, 223–247. http://dx.doi.org/10.1016/0378-3839(93)90003-Q.
- Khayyer, A., Gotoh, H., Shao, S.D., 2008. Corrected Incompressible SPH method for accurate water-surface tracking in breaking waves. Coast. Eng. 55, 236–250. http:// dx.doi.org/10.1016/j.coastaleng.2007.10.001.
- Kisacik, D., Troch, P., Van Bogaert, P., 2012. Description of loading conditions due to violent wave impacts on a vertical structure with an overhanging horizontal cantilever slab. Coast. Eng. 60, 201–226. http://dx.doi.org/10.1016/ j.coastaleng.2011.10.001.
- Lara, J.L., Ruju, A., Losada, I.J., 2010. Reynolds averaged Navier-Stokes modelling of long waves induced by a transient wave group on a beach. Proc. R. Soc. A Math. Phys. Eng. Sci. 467, 1215–1242. http://dx.doi.org/10.1098/rspa.2010.0331.
- Le Mehaute, B., 1976. An Introduction to Hydrodynamics and Water Waves. Springer-Verlag, New York vol. 8 + 323 p.
- Lin, P., Liu, P.L.-F., 1999. Internal wave-maker for Navier-stokes equations models. J. Waterw. Port. Coast. Ocean. Eng. 125, 207–215.

#### Coastal Engineering 127 (2017) 37-54

- Lind, S.J., Xu, R., Stansby, P.K., Rogers, B.D., 2012. Incompressible smoothed particle hydrodynamics for free-surface flows: a generalised diffusion-based algorithm for stability and validations for impulsive flows and propagating waves. J. Comput. Phys. 231, 1499–1523. http://dx.doi.org/10.1016/j.jcp.2011.10.027.
- Liu, Z., Frigaard, P., 2001. Generation and Analysis of Random Waves, Laboratoriet for Hydraulik Og Havnebygning. Instituttet for Vand, Jord og Miljoeteknik, Aalborg Universitet.
- Liu, P.L.-F., Lin, P., Chang, K.-A., Sakakiyama, T., 1999. Numerical modeling of wave interaction with porous structures. J. Waterw. Port. Coast. Ocean. Eng. 125, 322–330. http://dx.doi.org/10.1061/(ASCE)0733-950X(1999)125:6(322).
- Liu, X., Lin, P., Shao, S., 2015. ISPH wave simulation by using an internal wave maker. Coast. Eng. 95, 160–170. http://dx.doi.org/10.1016/j.coastaleng.2014.10.007.
   Liu, X., Lin, P., Shao, S., 2015. ISPH wave simulation by using an internal wave maker.
- Liu, X., Lin, P., Shao, S., 2015. ISPH wave simulation by using an internal wave maker. Coast. Eng. 95, 160–170. http://dx.doi.org/10.1016/j.coastaleng.2014.10.007.
- Liu, X., Shao, S., Lin, P., Tan, S.K., 2016. 2D numerical ISPH wave tank for complex fluid-structure coupling problems. Int. J. Offshore Polar Eng., (IJOPE) 26 (1), 26–32.
- Lo, E.Y.M., Shao, S., 2002. Simulation of near-shore solitary wave mechanics by an incompressible SPH method. Appl. Ocean. Res. 24, 275–286. http://dx.doi.org/ 10.1016/S0141-1187(03)00002-6.
- O.S. Madsen, On the generation of long waves, J. Geophys. Res. 76(1971) 8672–8683. http://doi.wiley.com/10.1029/JC076i036p08672 (Accessed February 17, 2017).
- Madsen, P.A., Sørensen, O.R., 1992. A new form of the Boussinesq equations with improved linear dispersion characteristics. Part 2. A slowly-varying bathymetry. Coast. Eng. 18, 183–204. http://dx.doi.org/10.1016/0378-3839(92)90019-Q.
- Coast. Eng. 18, 183–204. http://dx.doi.org/10.1016/0378-3839(92)90019-Q.Manenti, S., Panizzo, A., Ruol, P., Martinelli, L., 2008. Sph simulation of a floating body forced by regular waves. 3rd SPHERIC Work 38–41.
- Mansard, E.P.D., Funke, E.R., 1980. CHAPTER 8 the Measurement of Incident and Reflected Spectra Using a Least Squares Method by ABSTRACT a Least Squares Method to Separate the Incident and Reflected Spectra from the Measured Co-existing Spectra Is Presented. This method requires a simultan, pp. 154–172.
   McCabe, M., Stansby, P.K., Apsley, D.D., 2011. Coupled wave action and shallow-water
- McCabe, M., Stansby, P.K., Apsley, D.D., 2011. Coupled wave action and shallow-water modelling for random wave runup on a slope. J. Hydraul. Res. 49, 515–522. http:// dx.doi.org/10.1080/00221686.2011.566253.
- McCabe, M.V., Stansby, P.K., Apsley, D.D., 2013. Random wave runup and overtopping a steep sea wall: shallow-water and Boussinesq modelling with generalised breaking and wall impact algorithms validated against laboratory and field measurements. Coast. Eng. 74, 33–49. http://dx.doi.org/10.1016/j.coastaleng.2012.11.010.
- Meringolo, D.D., Aristodemo, F., Veltri, P., 2015. SPH numerical modeling of waveperforated breakwater interaction. Coast. Eng. 101, 48–68. http://dx.doi.org/ 10.1016/j.coastaleng.2015.04.004.
- Monaghan, J.J., 1992. Smoothed particle hydrodynamics. Annu. Rev. Astron. Astrophys. 30, 543–574.
- Ni, X.Y., Bin Feng, W., 2013. Numerical simulation of wave overtopping based on DualSPHysics. Appl. Mech. Mater. 405–408, 1463–1471 doi:10.4028/www. scientific.net/AMM.405-408.1463.
- Ni, X., Feng, W.B., Wu, D., 2014. Numerical simulations of wave interactions with vertical wave barriers using the SPH method. Int. J. Numer. Methods Fluids 76, 223–245. http://dx.doi.org/10.1002/fld.3933.
- Nwogu, O., 1993. Alternative form of Boussinesq equations for nearshore wave propagation. J. Waterw. Port. Coast. Ocean. Eng. 119, 618–638. http://dx.doi.org/ 10.1061/(ASCE)0733-950X(1993)119:6(618).
- P. Omidvar, P.K. Stansby, B.D. Rogers, SPH for 3D floating bodies using variable mass particle distribution, Int. J. Numer. Methods Fluids. 72(2013) 427–452. http://doi. wiley.com/10.1002/fld.3749 (Accessed February 15, 2017).
- Ottesen-Hansen, H., Sand, N.E., Lundgren, S.E., Sorensen, H., Gravesen, T., 1980. Correct reproduction of group-induced long waves. In: Proc. 17th Coastla Eng. Conf. American Society of Civil Engineers, pp. 784–800.
- Peregrine, D.H., 1967. Long waves on a beach. J. Fluid Mech. 27, 815–827. http:// dx.doi.org/10.1017/S0022112067002605.
- Peregrine, D.H., 2003. Water-wave impact on walls. Annu. Rev. Fluid Mech. 35, 23–43. Ploeg, E.R., Funke, J., 1985. The generation of laboratory waves: a tool for the understanding of wave dynamics. In: Proc. Int. Symp. Water Wave Res. SFB 205.
- Univ. Hann, Ger, pp. 265–283. Ren, B., Wen, H., Dong, P., Wang, Y., 2014. Numerical simulation of wave interaction
- with porous structures using an improved smoothed particle hydrodynamic method. Coast. Eng. 88, 88–100. http://dx.doi.org/10.1016/j.coastaleng.2014.02.006.
- Rogers, B.D., Dalrymple, R.A., Stansby, P.K., 2010. Simulation of caisson breakwater movement using 2-D SPH. J. Hydraul. Res. 48, 135–141. http://dx.doi.org/10.1080/ 00221686.2010.9641254.

- S.H. Salter, Absorbing wavemakers and wide tanks, in: Proceeding, Dir. Wave Spectra Appl. Berkeley, Calif., 1981: pp. 185 – 202.
- Sampath, R., Montanari, N., Akinci, N., Prescott, S., Smith, C., 2016. Large-scale solitary wave simulation with implicit incompressible SPH. J. Ocean. Eng. Mar. Energy 2, 313–329. http://dx.doi.org/10.1007/s40722-016-0060-8.Sand, S.E., 1982. Long waves in directional seas. Coast. Eng. 6, 195–208.
- Schäffer, H.A., 1996. Second-order wavemaker theory for irregular waves. Ocean. Eng. 23, 47–88. http://dx.doi.org/10.1016/0029-8018(95)00013-B.
- Schaffer, H.A., Klopman, G., 2000. Review of multidirectional active wave absorption methods. J. Waterw. Port. Coast. Ocean. Eng. 126, 88–97.
- Schäffer, H.A., Sørensen, O.R., 2006. On the internal wave generation in Boussinesq and mild-slope equations. Coast. Eng. 53, 319–323. http://dx.doi.org/10.1016/ j.coastaleng.2005.10.022.
- Schäffer, H.A., Steenberg, C.M., 2003. Second-order wavemaker theory for multidirectional waves. Ocean. Eng. 30, 1203–1231. http://dx.doi.org/10.1016/ S0029-8018(02)00100-2.
- Shadloo, M.S., Weiss, R., Dalrymple, R.A., 2015. Numerical Simulation of Long Wave Run-up for Breaking and Non-breaking Waves, vol. 25, pp. 1–7.
- Skillen, A., Lind, S., Stansby, P.K., Rogers, B.D., 2013. Incompressible smoothed particle hydrodynamics (SPH) with reduced temporal noise and generalised Fickian smoothing applied to body–water slam and efficient wave–body interaction. Comput. Methods Appl. Mech. Eng. 265, 163–173. http://dx.doi.org/10.1016/ j.cma.2013.05.017.
- St-germain, P., Nistor, I., Asce, M., Townsend, R., Shibayama, T., 2014. Smoothed-particle Hydrodynamics Numerical Modeling of Structures Impacted by Tsunami Bores, vol. 1, pp. 66–81. http://dx.doi.org/10.1061/(ASCE)WW.1943-5460.0000225.
- Suzuki, T., Altomare, C., Veale, W., Verwaest, T., Trouw, K., Troch, P., Zijlema, M., 2017. Efficient and robust wave overtopping estimation for impermeable coastal structures in shallow foreshores using SWASH. Coast. Eng. 122, 108–123. http://dx.doi.org/ 10.1016/j.coastaleng.2017.01.009.
- Taylor, K.E., 2001. Summarizing multiple aspects of model performance in a single diagram. J. Geophys. Res. 106, 7183–7192. http://dx.doi.org/10.1029/ 2000JD900719.
- Team, D., 2016. User Guide for DualSPHysics v4.0. http://www.dual.sphysics.org/index. php/downloads/.
- Troch, P., De Rouck, J., 1999. An active wave generating absorbing boundary condition for VOF type numerical model. Coast. Eng. 38, 223–247.
- Troch, P., De Rouck, J., 1999. An Active Wave Generating Absorbing Boundary Condition for VOF Type Numerical Model.
- Ursell, Y.S., Dean, F., Yu, R.G., 1960. Forced small-amplitude water waves: a comparison of theory and experiment. J. Fluid Mech. 7, 3–52. http://dx.doi.org/10.1017/ S0022112060000037.
- Vanneste, D., Troch, P., 2012. An improved calculation model for the wave-induced pore pressure distribution in a rubble-mound breakwater core. Coast. Eng. 66, 8–23.
- Vanneste, D., Altomare, C., Suzuki, T., Troch, P., Verwaest, T., 2014. Comparison of numerical models for wave overtopping and impact on a sea wall. In: Int. Conf. Coast. Eng. ASCE, Seoul, pp. 1–14.
- Violeau, D., 2012. Fluid Mechanics and the SPH Method: Theory and Applications. Vrijling, J.K., Van Gelder, P.H.A.J.M., 1999. Uncertainty Analysis of Non-breaking Waves.
- MAST III/PROVERBS. Final Report IIa (4.4). Wei, G., Kirby, J.T., 1995. Time-dependent Numerical Code for Extended Boussinesq
- Equations, vol. 121, pp. 251–261. Wei, Z., Dalrymple, R.A., Hérault, A., Bilotta, G., Rustico, E., Yeh, H., 2015. SPH modeling of dynamic impact of tsunami bore on bridge piers. Coast. Eng. 104, 26–42. http://
- dx.doi.org/10.1016/j.coastaleng.2015.06.008.
  Wen, H., Ren, B., Dong, P., Wang, Y., 2016. A SPH numerical wave basin for modeling wave-structure interactions. Appl. Ocean. Res. 59, 366–377. http://dx.doi.org/10.1016/j.apor.2016.06.012.
- Wendland, H., 1995. Piecewise polynomial, positive definite and compactly supported radial functions of minimal degree. Adv. Comput. Math. 4, 389–396. http:// dx.doi.org/10.1007/BF02123482.
- Williams, H.E., Briganti, R., Pullen, T., 2014. The role of offshore boundary conditions in the uncertainty of numerical prediction of wave overtopping using non-linear shallow water equations. Coast. Eng. 89, 30–44. http://dx.doi.org/10.1016/ j.coastaleng.2014.03.003.
- Zhang, H., Schäffer, H.A., Bingham, H.B., 2006. A method for generating highly nonlinear periodic waves in physical wave basins. In: Proceedings of the 21st International Workshop on Water Waves and Floating Bodies. Loughborough, UK.
- Zijlema, M., Stelling, G., Smit, P., 2011. SWASH: an operational public domain code for simulating wave fields and rapidly varied flows in coastal waters. Coast. Eng. 58, 992–1012. http://dx.doi.org/10.1016/j.coastaleng.2011.05.015.

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