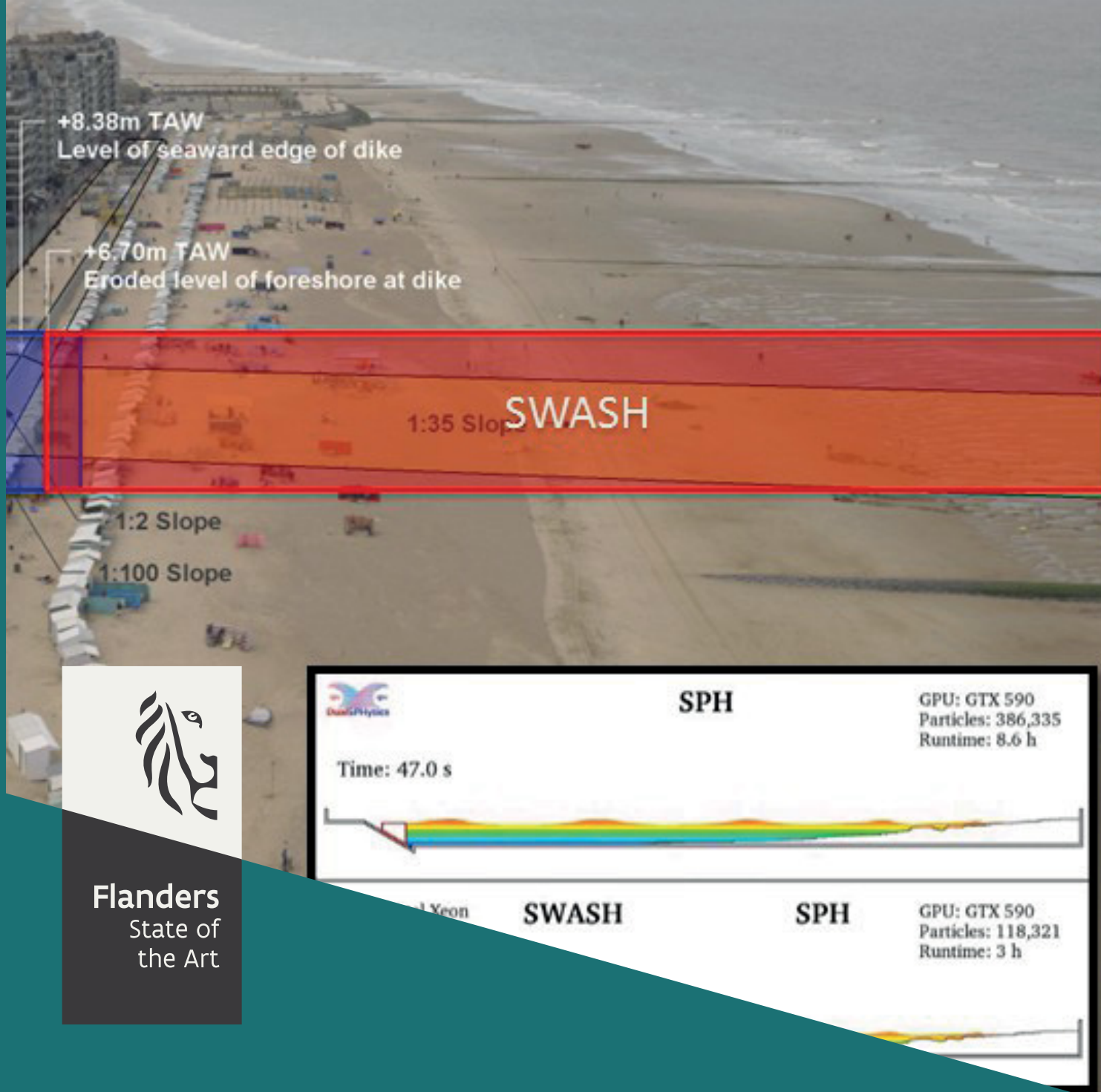




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WL rapporten

Optimized hybrid model for coastal safety assessment

Wave generation and absorption in DualSPHysics model,
1st-year Progress Report

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Altomare, C.; Gomez-Gesteira, M.; Vanneste, D.; Suzuki, T.; Peeters, P.; Mostaert, F.

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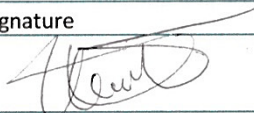
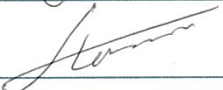
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Abstract

The present document represents a progress report of the first year of the 15_009 project on “Optimized hybrid model for coastal safety assessment”. This report describes briefly the achieved results and defines the targets for the next year.

Main aim of the first year was the implementation of an efficient, simple and accurate wave generation and wave absorption technique in DualSPHysics code as stand-alone model which was succeeded. The DualSPHysics model is now able to generate both long-crested monochromatic and random waves with a piston-type wavemaker. The active wave absorption system (AWAS) has been proved to be effective for monochromatic and random waves.

The implementation of the “wave absorption for hybridization” (AWAS-hy) and validation numerical and/or physical model results are foreseen for the next year, leaving the optimization of the pre-processing tool and the redaction of a detailed user guide for the third and last year.

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1 Introduction

The increasing number of large storm events along European coasts (e.g. Cyclone Xynthia, 2010; Cyclone Xavier, 2013) and ongoing sea level rise are great threats for low-lying countries. Therefore, the Flemish Government implements the Coastal Safety Master Plan to limit disasters in the coastal regions from future events. To do that in a cost-efficient way, accurate estimates of wave transformation, wave overtopping and wave forces on structures are necessary. However, representing all the processes that characterize the waves acting on coastal structures is highly challenging by means of only one numerical model: i.e. waves propagate from offshore to coastal defence lines experiencing major changes in a large spatial domain, at the same time waves experience rapid temporal changes interacting with the coastal defences in a small spatial domain.

Numerical models have their own specific capabilities and shortcomings. A fast and reliable model able to study the wave propagation (large spatial domains and long-time durations), often is not accurate at more detailed scales to characterize the effects of the wave on the structures. Models which are capable to catch the details of that interaction are not suitable to be used for very large domains because computationally too expensive. Hence, it appears mandatory to implement a strategy using two different models together. This strategy can provide a tool capable of representing all the phenomena above mentioned.

Flanders Hydraulics Research has defined a strategy to hybridize two different and complementary numerical models, namely SWASH (Zijlema et al., 2011) and DualSPHysics (Crespo et al., 2015). The first results of the implemented hybridization technique have been recently published in an international peer-reviewed journal (Altomare et al. 2015b). This is the results of several efforts made during the last 3.5 years (in collaboration with, some REFs ...).

The hybridization strategy between the SWASH and the DualSPHysics models has been implemented mainly within the framework of FHR project 13_027, which phases can be summarized as follows:

- a) Development of the most appropriate hybridization technique (hybridization points, quantities to be passed from one model to the other, etc).
- b) Implementation of the hybridization technique.
- c) Validation with cases of wave propagation over low reflective beach profiles (Altomare et al., 2015b).
- d) Validation with cases of wave overtopping and impact in shallow foreshore conditions using data from scale model tests conducted at Flanders Hydraulics Research (Altomare et al., 2015c).

The development of the hybridization strategy within the framework of the WL 13_027 project together with the latest works on DualSPHysics applied to coastal structures (Barreiro et al, 2013; Altomare et al., 2014; Altomare et al., 2015a) have represented an advance in the SPH-modelling of wave-structure interaction for research and consultancy purposes. However there were still significant limitations that need to be overcome. Among them, it was necessary to cope with the re-reflected waves, that otherwise can add unrealistic energy into the domain and bias the results of the simulation. Such objective is normally achieved in physical modelling by means of Active Wave Absorption Systems (AWAS). Thereby the main purpose of the present project was to implement the required techniques to treat the wave reflection in the DualSPHysics domain.

Seven different tasks have been defined for the present project. The timeframe or work load of the project consists of 3 years work. Each year, some of the tasks are executed. The tasks are:

1. Literature review of the existing Active Wave Absorption Systems that are used both in physical and numerical wave models. (1st year)

2. Identification of the AWAS technique/s to be implemented in DualSPHysics as stand-alone model. (1st year)
3. Implementation and validation of the AWAS technique/s with selected benchmark cases. (1st year)
4. Identification of the best strategy to absorb the re-reflected waves in the hybridized SWASH-DualSPHysics model. (1st year)
5. Implementation of the “wave absorption for hybridization” (AWAS-hy) and validation of the 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) (2nd year)
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). (3rd year)
7. Redaction of the user manual that can guide step by step in the application of the hybridization strategy for 2D and 3D cases. (3rd year)

In the end of this project, we will have a tool capable of modelling the wave-structure interaction in an optimized, low-cost, and fast way. This model will be an important tool to answer further problems, where for example, the 3D effects of complex structural geometries on wave overtopping and overflows are important, and flow patterns, velocity fields, loadings, etc. need to be characterized.

2 1st year results

The main results achieved during the 1st year of the project are here summarized. The full details are provided in Altomare et al. (2015d). The paper from Altomare et al. (2015d) is included in the present document as external annex (see section 2.4).

2.1 Wave generation

The waves are generated in DualSPHysics by means of moving boundaries that aim to mimic the movement of a wavemaker as in physical facilities. The wave generation using moving boundary in DualSPHysics consists of piston- and also flap-type wave-makers.

First and second order wave generation theories are implemented in DualSPHysics. The first order generation is fully described in Altomare et al. (2015d), and it's used for monochromatic waves. Random waves are generated by means of a first order wave generation theory. For second order wave generation, the reader is referred to the solution proposed by Madsen (1971) where the author advises to use it only for $HL^2/d^3 < 8\pi/3$, where H and L are the wave height and wavelength respectively (referred to a case of monochromatic waves) and d is the water depth at the wave-maker location in still water conditions.

The first order wave generation for monochromatic waves is extended to random waves in DualSPHysics based on the method described in Liu and Frigaard (2001). Two standard wave spectra are implemented and used to generate random waves: JONSWAP and Pierson-Moskowitz spectra. The generation system allows having different random time series with the same significant wave height (H_{m0}) and the same peak period (T_p), just defining different phase seeds.

In this way, wave height, wave period and depth are the key input parameters in DualSPHysics, therefore the time series of wavemaker displacement is computed using the aforementioned wave theory. Only the piston-type is used in this work.

A second order wave generation for random waves is currently under development, based on Sand and Donslund (1985) which introduced correction equations for bounded long waves.

2.2 Active wave absorption

Active wave absorption is used in physical facilities to absorb the reflected waves at the wave-maker in order to avoid that they will be reflected back into the domain. In this way, the active absorption prevents the introduction into the system of extra spurious energy that will bias the results. With active absorption, the position of the wave maker is corrected every time step.

The active wave absorption system (AWAS) implemented in DualSPHysics is based on the approach described in Schäffer and Klopman (2000). The water surface elevation η at the wavemaker position is used and transformed by an appropriate time-domain filter to obtain a control signal that corrects the wave paddle displacement in order to absorb the reflected waves every time step.

Hence, the target wave-maker position is corrected to avoid reflection at the wave-maker. The position in real time of the wave-maker is obtained through the velocity correction of its motion. For a piston-type wave-maker the velocity correction is calculated using linear long wave theory in shallow water (Didier and Neves, 2001; Schäffer and Klopman, 2000). For that it is necessary to estimate the free-surface elevation of the reflected waves, η_R , to be absorbed comparing the target incident water surface elevation, η_i , with the measured one in front of the wave-maker, η_{SPH} . The corrected wave-maker velocity is then the summation

of velocity correction and the theoretical incident wave-maker velocity. For further details, the reader is referred to Altomare et al. (2015d).

2.3 Wave absorption for hybridization

Possible techniques have been discussed to cope with re-reflected waves in the hybrid SWASH-DualSPHysics model. Finally an active wave absorption system has been selected, similar to that used in DualSPHysics as stand-alone model (see previous section). The only difference is in the target incident water surface elevation, η_i : in DualSPHysics this is the theoretical water surface elevation; in SWASH-DualSPHysics it will be the same water surface elevation measured in SWASH prior the hybridization. Therefore SWASH output will be used as to “steer” the moving boundary in DualSPHysics to generate the desired waves and, once again, to correct the moving boundary displacement when the re-reflection starts to occur.

Full details of the implementation will be part of the Progress Report for the 2nd year of the project.

2.4 Published work

For full details on the implemented techniques for wave generation and wave absorption in DualSPHysics, refer to Altomare et al. (2015d). The paper is attached in Appendix 1.

3 Conclusions and future work

An efficient, simple and accurate wave generation and wave absorption technique has been implemented in DualSPHysics code as stand-alone model. The results have been presented by Altomare et al. (2015d), proving the accuracy of the implemented method.

DualSPHysics model is now able to generate both long-crested monochromatic and random waves with a piston-type wavemaker. The active wave absorption system (AWAS) has been proved to be effective for monochromatic and random waves. A similar approach will be used to treat the re-reflection in the hybrid SWASH-DualSPHysics model.

The main task for the next year of the project will be therefore the implementation of the “wave absorption for hybridization” (AWAS-hy) and validation of numerical and/or physical model results.

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Appendix 1 Altomare et al. (2015d)

Numerical wave dynamics using Lagrangian approach: wave generation and passive & active wave absorption

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Abstract— SPH has been applied to the study of free surface problems with good accuracy for wave propagation and wave-structure interaction. This work describes the implementation of a 1st order wave generation system, capable of generating both monochromatic (regular) and random waves in SPH codes. To verify the proper wave propagation, the implementation of a wave absorption system is mandatory. The use of wave absorption techniques allows generating long time series of sea waves in relatively short domains with negligible wave reflection. The wave absorption can be passive or active: both are implemented in DualSPHysics. Results of the implemented wave generation, passive absorption and active absorption systems are validated with theoretical solutions showing very good accuracy in terms of wave surface elevation and reflection coefficients.

I. INTRODUCTION

SPH is becoming more and more popular among researchers in coastal engineering. The application of SPH-based models to study sea waves interacting with beaches and coastal defences has increased during the last few years (e.g. [1-5]). The meshless nature of an SPH-based model allows catching the violent hydrodynamics of the sea waves that, propagating towards the shoreline, break, run-up and overtop sea dikes or breakwaters.

A computational model can be considered as a numerical representation of a physical wave flume or wave basin, where waves are generated by means of a single or a multiple wave paddle (usually piston and flap-type). Specific algorithms are implemented to define the wave paddle movement to generate representative waves of the reality. Furthermore passive and/or active absorption systems are usually implemented in the physical facilities, to avoid unrealistic wave re-reflection by the boundaries of the domain that would introduce an extra energy biasing the results of the physical modelling. Similarly, it is mandatory to guarantee a correct wave generation and wave energy absorption in numerical models. Although there is already plenty of literature on the application of SPH to coastal engineering problems as far as we know, a fully detailed

description of the implemented wave generation and absorption is often missing.

Therefore a proper wave generation algorithm has been implemented in DualSPHysics ([6]), together with passive and active absorption system. DualSPHysics has been recently applied to free-surface flow problems and it has been proven to give accurate results in agreement with physical model and in-situ data ([4,7]), however its applicability was limited by the lack of a proper wave absorption and optimised wave generation system. The code had the possibility to introduce regular, linear or sinusoidal movement to any object in order to mimic the wave generators, but that procedure was not optimised for coastal engineering purposes (e.g. the modelling of standard wave spectra for random waves was not possible and the time series of paddle displacement had to be created externally and imported).

With the implementation of a wave generation algorithm, sea waves can be now generated by means of a numerical wave paddle that can be modelled both as piston (horizontal displacement) and flap (rotational movement). The final user of the code will find now a proper and easy way to define which kind of wave characteristics (monochromatic and spectra-defined waves) to be simulated in the numerical model. This will be equivalent to the 1st order wave generation that is implemented in any physical model facility worldwide.

Furthermore, the use of wave absorption allows generating long time series of sea waves in relatively short domains with negligible wave reflection. Otherwise, a very long, and computationally too expensive, numerical domain should be built to avoid a certain number of waves re-reflecting on the wave generator.

The final aim is to have a numerical wave facility as accurate as possible. The details of the implemented wave generation systems, passive absorption and active absorption are described and validated with theoretical solutions in this work.

II. WAVE GENERATION

The first step has been the implementation of a 1st order wave generation system, capable of generating both monochromatic (regular) and random waves, using either piston or flap wave-makers. The wave generation was verified and compared against theoretical results and it was optimised to get the target wave spectrum and wave time series. Only long-crested waves are generated at this stage.

Hence the following sections will describe the theory behind the technique to generate monochromatic and random waves using a SPH piston-type wave generator.

A. Theoretical notes

The Biesel transfer functions express the relation between wave amplitude and wave paddle displacement ([8]), under the assumption of irrotational and incompressible fluid and constant pressure at the free surface. The transfer function links the displacement of the piston-type wave generator to the water surface elevation, under the hypothesis of monochromatic sinusoidal waves:

$$\eta(x, t) = c \cdot \sinh(kd) \cos(\omega t - kx + \delta) + \sum_{n=1}^{\infty} c_n \sinh(k_n d) e^{-k_n x} \sin(\omega t) \quad (1)$$

where c , c_n and k_n are coefficients depending on the paddle type, paddle cycling frequency and water depth. The quantity $\omega = 2\pi/T$ is the angular frequency, d the water depth, $k = 2\pi/L$ is the wave number with T equal to the wave period and L the wave length. The initial phase δ is given by a random number between 0 and 2π .

The first term in Eq. (1) expresses the surface elevation at infinity that Biesel defined as the far-field solution. In general only the far-field solution is interesting because the amplitude of a linear wave should not change with location. The second term is the near-field solution (representing a series of standing waves near the piston in phase with the piston movement). For further details see [8]. According to [9], the disturbance from the near-field solution is generally less than 1% of the far-field solution at a distance of approximately one to two wave lengths far from the piston and hence it can be neglected. Therefore the Biesel function can be derived for the far-field solution as:

$$c \cdot \sinh(kd) = \frac{H}{2} \quad (2)$$

where H is the wave height. For a piston-type wave-maker the Biesel transfer function can be expressed as follows:

$$\frac{H}{S_0} = \frac{2 \sinh^2(kd)}{\sinh(kd) \cosh(kd) + kd} \quad (3)$$

where S_0 is the piston stroke. Once the piston stroke is defined, the time series of the piston movement is given by:

$$e(t) = \frac{S_0}{2} \cos(\omega t + \delta) \quad (4)$$

The defined Biesel transfer function allows generating wave trains of monochromatic sinusoidal waves. The method described in [10] is used in DualSPHysics to generate irregular waves. This method starts from an assigned wave spectra and applies the Biesel transfer function to each component in which

the spectrum is divided. The procedure to generate irregular waves can be summarised as follows:

1. Define the wave spectrum through its characteristic parameters (peak frequency, spectrum shape, etc.). An example of wave spectrum is shown in Figure 1, where the y-axis represents the spectrum density and the x-axis the frequency ($=1/T$).
2. Divide the spectrum in N parts ($N > 50$) in the interval (f_{start}, f_{stop}) , where generally the values assumed by the spectrum (S_{η}) at the extremes of this interval is smaller than the value assumed for the peak frequency, f_p : $S_{\eta}(f_{start}) \leq 0.01 \cdot S_{\eta}(f_p)$ and $S_{\eta}(f_{stop}) \leq 0.01 \cdot S_{\eta}(f_p)$.
3. The frequency band width is so-defined as $\Delta f = (f_{stop} - f_{start})/N$. The irregular wave is so decomposed into N linear waves.
4. Determine the angular frequency ω_i , amplitude a_i and initial phase δ_i (random number between 0 and 2π) of each linear wave:

$$f_i = f_{start} + i\Delta f - \Delta f/2 \quad (5)$$

$$\omega_i = 2\pi f_i \quad (6)$$

$$a_i = \sqrt{2S_{\eta}(f_i)\Delta f} = \frac{H_i}{2} \quad (7)$$

5. Convert the time series of surface elevation into the time series of piston movement with the help of Biesel transfer function:

$$\frac{H_i}{S_{0,i}} = \frac{2 \sinh^2(k_i h)}{\sinh(k_i h) \cosh(k_i h) + k_i h} \quad (8)$$

6. Compose all the components derived from the previous equation into the time series of the piston displacement as:

$$e(t) = \sum_{i=1}^N \frac{S_{0,i}}{2} \cos(\omega_i t + \delta_i) \quad (9)$$

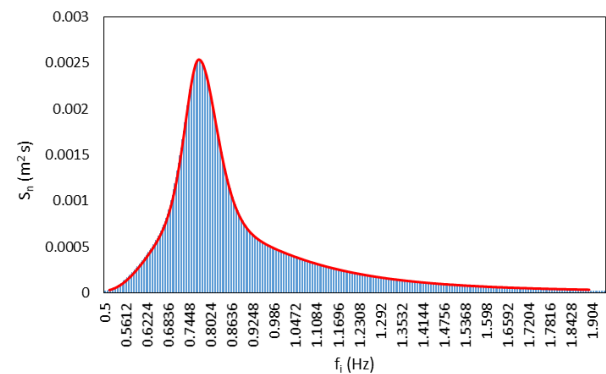


Figure 1. Example of standard wave spectra.

In DualSPHysics two standard wave spectra are implemented and used to generate irregular waves; JONSWAP and Pierson-Moskowitz spectra. The characteristic parameters of each spectrum can be assigned by the user together with the value of N (number of parts in which the spectrum is divided). A phase seed is also used and can be changed to have different random series of δ_i . Therefore changing the phase seed allows

generating different irregular wave time series both with the same significant wave height (H_{m0}) and peak period (T_p).

B. Implementation with SPH

The wave generation in DualSPHysics mimics the conditions of physical wave facilities. The wave-maker (piston or flap) consists of a rigid body formed by boundary particles. The motion of the wave generator is prescribed controlling its position (linear or angular) at each instant of time. In this work all the analysis is performed using only the piston-type wave-maker (i.e. wave generator with frontal vertical face moving horizontally on the flume bed).

C. Results with DualSPHysics

The wave generation so-implemented in DualSPHysics has been used for regular and random waves comparing the numerical results with theoretical solutions of water surface elevation and orbital velocities.

A very simple test case has been designed, where a piston wave-maker generates waves in a tank that ends with a vertical wall. The bottom of the tank is fully horizontal (Figure 2). The water depth d is 0.27m.

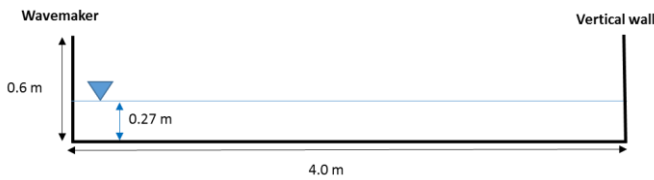


Figure 2. Setup of the test case.

The generated waves are:

- Regular waves: $H=0.1\text{m}$, $T=1.3\text{s}$.
- Irregular waves: $H_{m0}=0.1\text{m}$, $T_p=1.3\text{s}$ (JONSWAP spectrum).

The resulting wave length L is equal to 1.89m for regular waves. Similarly, in case of random waves, the peak wave length can be calculating using the peak period, T_p . Two tanks with different lengths have been modelled; a tank 4m long (depicted in Fig. 2) and a larger one of 35m. A similar case with 4m wave tank was reported in [11]. In the first tank, it is expected that the wave reflection on both-sides of the tank (piston and the vertical wall) appears after a few seconds, since the wave length (1.89m) and the domain size (4m) are comparable. Re-reflection is the phenomenon that occurs when the waves, once reflected from structure (in this case a vertical wall) come back towards the wave paddle and are reflected towards the structure. The case of the wave tank 35m long guarantees that re-reflection from the piston can be avoided during the first 30s.

Simulations are executed with DualSPHysics using a GPU card "GeForce GTX TITAN" to accelerate the calculations. An initial interparticle distance of $dp=0.004\text{m}$ leads to 65,934 fluid particles for the 4m long tank and 577,434 particles for the 35m long one and the simulation of 30s of physical time took 62.75 and 206.87 minutes for regular waves respectively.

The water surface elevation was measured at $x=2\text{m}$ from the wave paddle and the results were compared with theoretical solutions. The orbital horizontal and vertical velocities were

measured at 0.15m below the still water level. Figures 3 and 4 show respectively the water surface elevation and orbital velocities for the regular wave case. The results from the 35m long wave tank match the theoretical solution, proving that the waves are properly generated and there is no reflection. In the case of the 4m long wave tank the wave behaviour diverges from the theoretical one because of the wave reflection on both sides of the tank.

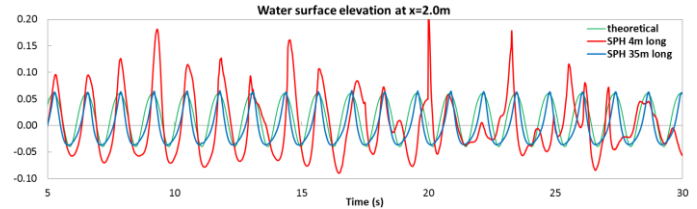


Figure 3. Comparison between theoretical and numerical water surface elevation for regular waves.

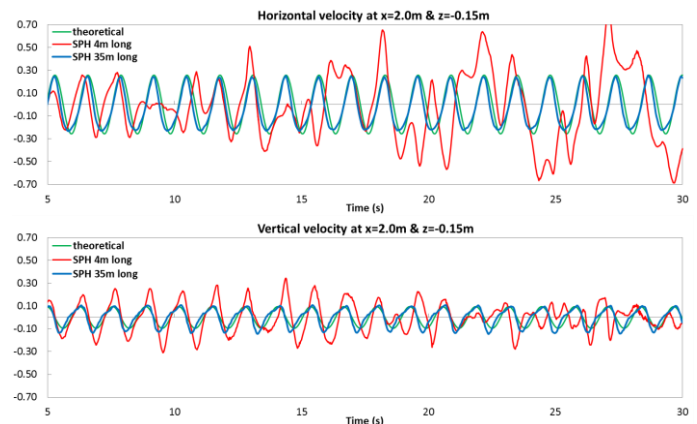


Figure 4. Comparison between theoretical and numerical horizontal (upper panel) and vertical (lower panel) velocity with regular waves.

Similar results are obtained for the irregular wave case (Figure 5). Some differences can be noticed between the 35m wave tank case and the theoretical solution. The reason of this difference is twofold: on the one hand, it might depend on the numerical modelling resolution and on the other hand, it is important to notice that the selected theoretical wave conditions correspond to waves between 2nd and 3rd order based on the regions of validity of wave theories by [12], however a 1st order wave generation is implemented. Therefore the waves in the numerical model are characterised by that non-linearity proper of 2nd and 3rd order waves, meanwhile the theoretical solution is calculated as 1st order waves.

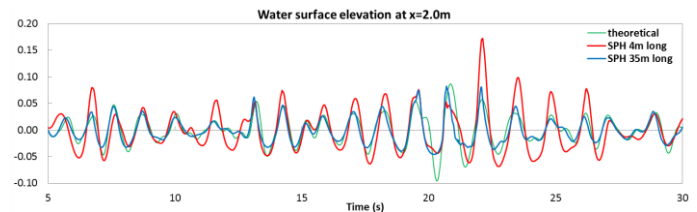


Figure 5. Comparison between theoretical and numerical water surface elevation for irregular waves.

III. 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 “sponge” area: both have been implemented and checked in DualSPHysics. A dissipative beach is usually a kind of passive absorption system that is used in physical model tests. Dissipative beaches are systems where most wave energy is expended through the process of breaking. The beach can have a straight or parabolic shape. The former one is implemented in DualSPHysics, where the angle of the beach with respect to the horizontal is constant for the entire extension of it.

The sponge area consists of reducing the velocity of the particles following

$$v_i^{new} = f(x_i) \cdot v_i \quad (10)$$

where v_i is the velocity of the particle i that enter this area and

$$f(x_i) = \min\left(1, \left(1 - \frac{L_s - x_0 - x_i}{L_s}\right)^5\right) \quad (11)$$

where L_s is the length of the sponge area and x_0 the initial position.

The model has now been defined to resemble the one described in the previous section (the same water depth and wave characteristics) with the difference that the vertical wall at the end of the wave tank is replaced by a dissipative beach (11.3°) or a “sponge” area (with $L_s=10\text{m}$ and $x_0=3\text{m}$). The sketches of the models with passive wave absorption systems are depicted in Figure 6.

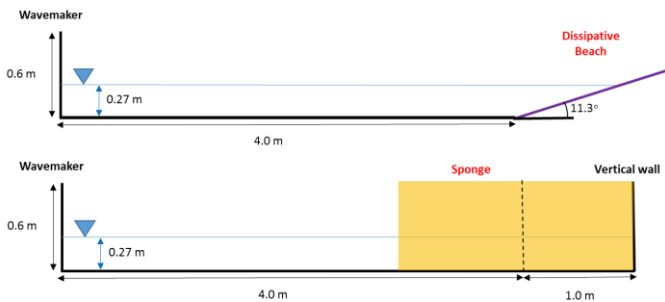


Figure 6. Setup of the test case with dissipative beach (up) and sponge layer (down)

The idea now is to avoid reflection without using a large domain of 35m. Therefore we introduce these passive absorption systems in the 4m long wave tank. Figure 7 compares the theoretical and numerical water surface elevation measured at $x=2\text{m}$ where cases with dissipative beach and “sponge” area are reported. The same results calculated for the orbital velocities are plotted in Figure 8. A good agreement is observed between numerical results and theoretical solutions.

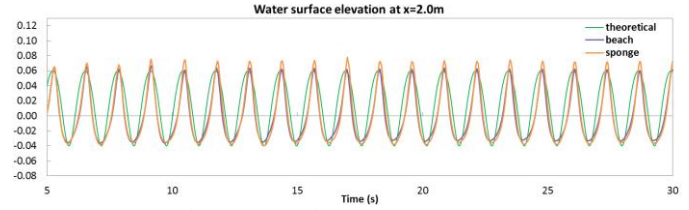


Figure 7. Water surface elevation for regular waves using a dissipative beach and a sponge layer.

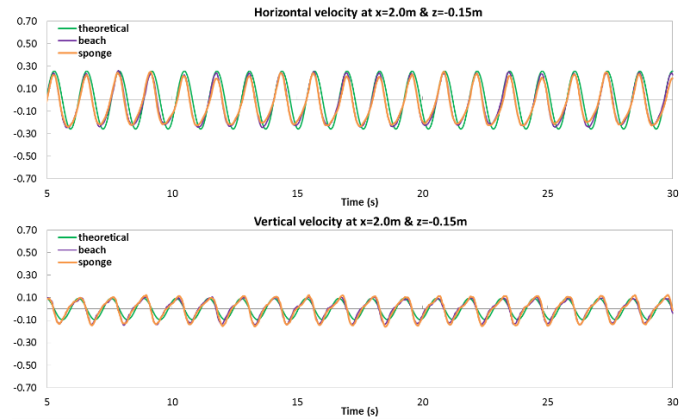


Figure 8. Comparison between theoretical and numerical horizontal (upper panel) and vertical (lower panel) velocity with regular waves using a dissipative beach and a sponge layer.

A snapshot taken at $t=22.2\text{s}$ in the numerical simulation is shown in Figure 9; the case without absorption and a domain size of only 4m is depicted with both absorption configurations. The results confirm the effectiveness of the implemented absorption systems for monochromatic waves: the simulation without any absorption is far from being representative of monochromatic waves, as also discussed in the previous section.

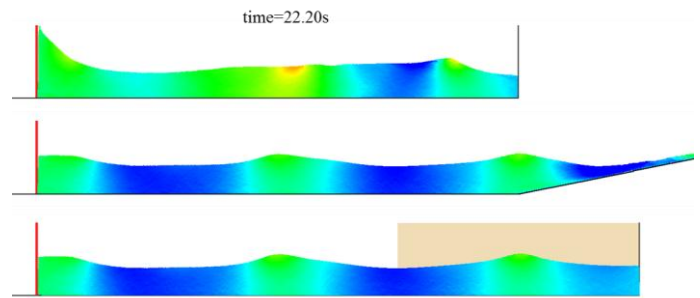


Figure 9. Instant (time=22.2s) of the simulation with regular waves and using dissipative beach and sponge layer.

The performance of the passive absorption has also been verified for irregular waves. The results are plotted in Figure 10. The water surface elevation measured with DualSPHysics for the dissipative beach and “sponge” area are compared with the theoretical solution (upper panel of Fig. 10) and with the results of the case with 35m long wave tank (bottom panel of Fig. 10). It can be noticed how the use of each passive absorption system leads to results that match the case of a very long domain, which is free of reflection during the first 30s.

The reflection coefficient (the ratio of the amplitude of the reflected wave and the amplitude of the incident wave) has been estimated in each case and values are reported in Table I. Coefficients without passive absorption are close to 100% (theoretical value for a vertical wall) and for the dissipative beach and the “sponge” coefficients are lower as expected. It can be noticed that for random waves the efficiency of the absorption decreases, even though the results can still be considered acceptable (a reflection coefficient of about 15-20% can be considered characteristic of low reflected systems). Modifying the length of the sponge area (L_s) or the slope of the beach will reduce further the wave reflection for irregular waves since the wave components with longest period will be more efficiently absorbed.

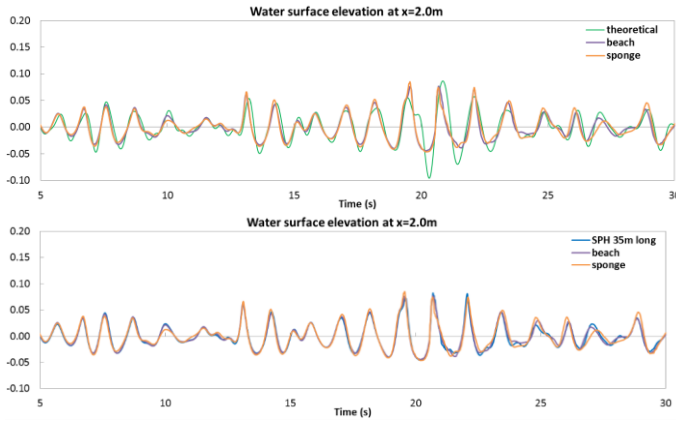


Figure 10. Water surface elevation for irregular waves using a dissipative beach and a sponge layer.

TABLE I. REFLEXION COEFFICIENTS

Target wave	No passive absorption	Beach	Sponge
$H=0.1\text{m}, T=1.3\text{s}$	99.9%	6.9%	4.5%
$H_{m0}=0.1\text{m}, T_p=1.3\text{s}$	97.6%	17.7%	20.1%

IV. ACTIVE WAVE ABSORPTION

When a highly reflective structure is modelled to study its interaction with sea waves (wave forces, structural stability, overtopping), the passive absorption technique is not feasible anymore. Methods for wave generation with active wave absorption were originally developed for physical wave flume experiments. The basic idea was that the reflected energy must be absorbed by the same wave generator, whose movement is modified to cancel out the reflected waves. This kind of absorption is called Active Wave Absorption System (AWAS). Following [13] and [14], the development of AWAS has been conducted using different approaches whose inputs are: i) water surface elevation (AWAS- η) or ii) velocity (AWAS- v) in front of the piston. These two kind of active absorption differ basically in two aspects: measured signal and filter type.

The water surface elevation η is used in AWAS- η and transformed by an appropriate time-domain filter to obtain a control signal that corrects the wave paddle displacement in order to absorb the reflected waves. The reflected wave signal is in general determined as the difference between the

measured surface elevation and the generated surface elevation estimated from the wave generator control signal.

On the other hand, the orbital horizontal and vertical velocities at a fix location inside the fluid domain are measured and used in AWAS- v where the digital FIR (finite impulse response) filters are used as described by [14] and [15]. This kind of active wave absorption system is based on real time separation of the wave field in front of the paddle in incident and reflected waves.

A. Theoretical notes on AWAS- η

The methodology proposed by [13] is followed to include the active wave absorption system (AWAS) in DualSPHysics model as AWAS- η . The target wave-maker position $e(t)$ is corrected in real time in order to avoid reflection at the wave-maker. The position in real time of the wave-maker is obtained through the velocity correction of its motion. For that it is necessary to estimate the free-surface elevation of the reflected waves, η_R , to be absorbed comparing the target incident water surface elevation, η_I , with the measured one in front of the wave-maker, η_{SPH} . This is measured at $5*dp$ from the wave-maker. Hence the reflected water surface elevation results:

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

The wave-maker velocity has to be modified to match the velocity induced by the wave that will be absorbed. For a piston-type wave-maker, characterised by uniform horizontal velocity along the water depth, the wave absorption is performed using linear long wave theory ([11,13]). The velocity correction to absorb the reflected waves, U_R , can be expressed as follows:

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

where η_R is the free-surface elevation of the reflected waves, g is the gravitational acceleration and d the water depth.

B. Implementation with SPH

The corrected wave-maker velocity U_C is the summation of U_R (Eq. 13)) and the theoretical or incident wave-maker velocity U_T . This U_T is the derivative in time of the wave-maker 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:

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

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

$$U_C(t + dt) = U_I(t) + U_R(t) \quad (15)$$

The wave-maker position at $t+dt$ is then corrected using the following expression:

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

A sketch of the active wave absorption system is depicted in Figure 11. The water surface elevation η_{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 is added to the theoretical velocity U_I into the “servo box” system that controls the paddle movement. The final result is the corrected wave paddle displacement $e(t+dt)$.

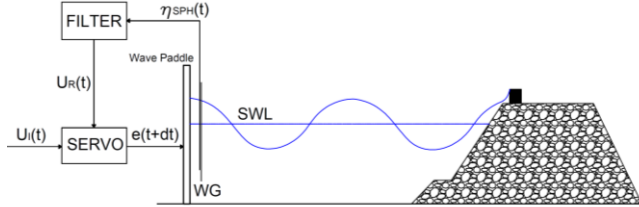


Figure 11. Definition sketch of AWAS system

C. Results with DualSPHysics. Test case 1

The same numerical model as in Figure 2 has been used to test the AWAS- η . The waves were generated by a piston-type wave-maker and reflected on a vertical and fully reflective wall. Both regular and random waves have been modelled. The wave characteristics and the water depth are the same as described in previous sections. Differently from the passive absorption (where the wave energy is smoothed at the end of the domain, so no waves are reflected back to the wave-maker), the use of the active absorption system aims to avoid re-reflection from the wave-maker, but not from the structure located on the other side of the domain (a vertical wall in this case).

Results for regular waves are shown in Figure 12 where the time series of the piston displacement and water surface elevation at $x=2m$ are depicted, respectively. The wave-maker position is varying during the first 13s of simulation to adapt itself to the different wave conditions. After this time, the wave-maker motion returns to be regular, so that the wave pattern is also stabilised.

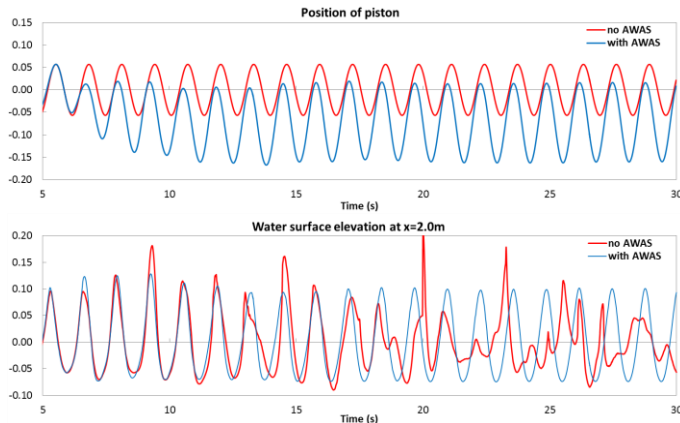


Figure 12. Piston position (upper panel) and water surface elevation (lower panel) for regular waves with and without AWAS.

The final mean position of the wave-maker is drifted from the initial one because of small deviation from 0 of the mean water surface at the front of the wave-maker. This behaviour is also noticed in [11,13]. However this drift only causes a difference in water level of 0.004m (2% of the water depth and similar to dp) that can be neglected. The water surface

elevation, after this transitional phase, becomes regular. The wave amplitude is higher than the target one because a standing wave regime is established inside the domain (lower panel in Figure 12). The incident wave height was also calculated (see Table II).

The behaviour and the applicability of AWAS can be also analysed in terms of the force exerted by the wave train on the vertical wall at the end of the tank. Figure 13 shows the time series of forces (including the hydrostatic component) exerted by the regular waves with and without AWAS on the wall. It can be observed how there is no difference between the two signals during the first 8 seconds, whereas, after that, only the force measured in the case with AWAS still presents a regular and periodic shape (in agreement with the time series of the water surface elevation shown in Figure 12). The time series of forces in the case without absorption is totally biased by the wave re-reflection.

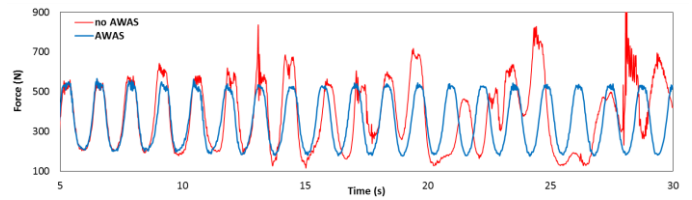


Figure 13. Wave force exerted on the vertical wall with and without AWAS.

A snapshot at the instant equal to 22.2s of the numerical simulation is shown in Figure 14. The upper panel of the figure corresponds to the case without active absorption and a chaotic water surface is observed (incident + reflected + re-reflected waves) while bottom panel shows the regular pattern with only incident and reflected wave when using AWAS.

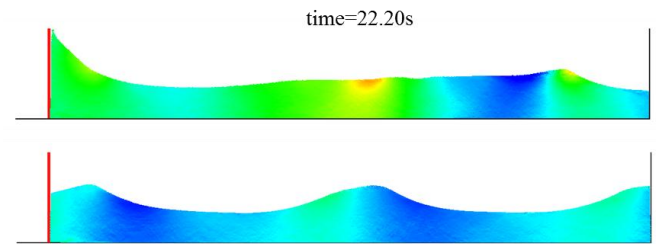


Figure 14. Instant (time=22.2s) of the simulation with regular waves without (up) and using AWAS (down).

Results for the irregular wave case are shown in Figure 15. It is less evident to assess the performance of the system only looking at the time series of free surface elevation, being the phenomenon characterised by a series of irregular waves. Hence, only the separation of incident and reflected waves can provide an estimation of the accuracy of the technique.

The reflection analysis has been carried out using the software WaveLab v.3.54 from Aalborg University. Results are shown in Table II. The incident wave height using AWAS- η is close to the target one meanwhile the lack of active absorption leads to values higher than the target since the re-reflected waves introduce more energy into the system. Furthermore, for random waves, the wave peak period is also affected by the re-

reflection, being higher than the target peak period when no absorption is used.

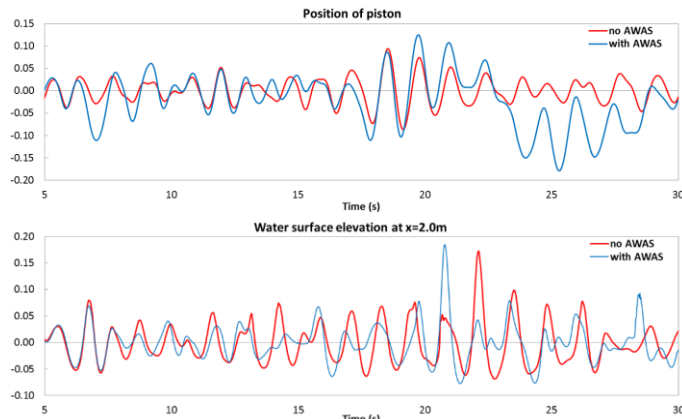


Figure 15. Piston position (upper panel) and water surface elevation (lower panel) for irregular waves with and without AWAS.

TABLE II. RESULTS OF ACTIVE ABSORPTION FOR TEST CASE 1

Target wave	Absorption	Incident wave height	Wave period
$H=0.100\text{m}$ $T=1.3\text{s}$	None	0.118m	1.28s
	AWAS- η	0.105m	1.28s
$H_{m0}=0.100\text{m}$ $T_p=1.3\text{s}$	None	0.134m	1.37s
	AWAS- η	0.095m	1.28s

D. Results with DualSPHysics. Test case 2

A second case has been tested with AWAS- η . The new case includes a 1:2 slope at the end of the numerical domain (Figure 16). The slope has been chosen to be representative of classical sea dikes. The reflection coefficient of such structure can be easily estimated using formula from literature (e.g. [16]) and it ranges from 55% to 60%.

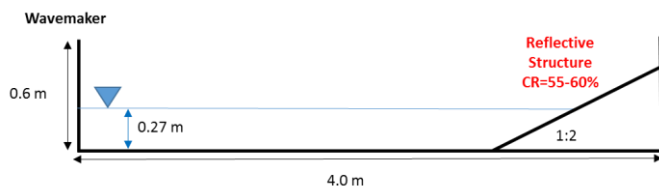


Figure 16. Setup of the test case 2 with 1:2 slope at the end.

The same wave conditions as in previous cases have been tested. The time series of water surface elevation for regular and irregular waves are shown in Figure 17 and 19, respectively.

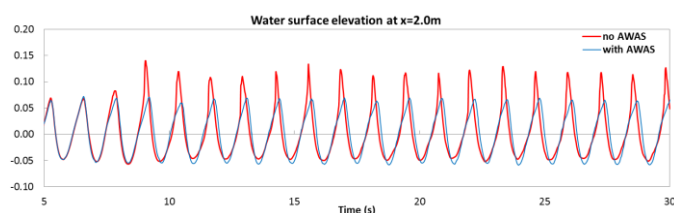


Figure 17. Water surface elevation (test case 2) for regular waves with and without AWAS.

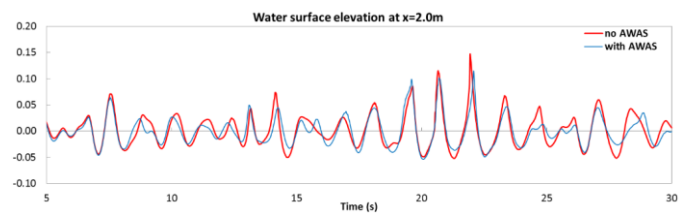


Figure 18. Water surface elevation (test case 2) for irregular waves with and without AWAS.

The performance of AWAS- η was estimated calculating the incident wave conditions through a wave reflection analysis. The results of incident wave height and reflection coefficients are reported in Table III. The numerical reflection coefficients are very similar to the theoretical one (55-60%).

TABLE III. RESULTS OF ACTIVE ABSORPTION FOR TEST CASE 2

Wave conditions	Absorption	Incident wave height	Reflection coefficient
Regular	None	0.110m	62.4%
	AWAS- η	0.099m	51.7%
JONSWAP	None	0.096m	62.8%
	AWAS- η	0.091m	57.8%

V. CONCLUSIONS

Wave generation and wave absorption have been successfully implemented in DualSPHysics ([video](#)). The comparisons of the absorption systems, presented in this work, with theoretical results prove the reliability of the implementation. Thanks to this reliability in sea wave modelling, DualSPHysics is gradually becoming an alternative or complementary tool to physical models.

The next step will be focused on the validation of AWAS- η with systems implemented in physical facilities, usually based on digital FIR filters ([14],[15]). In order to achieve this goal, the AWAS-v approach needs to be further analysed since it was successfully applied to mesh-based methods such as VOF or Flow3D but some issues related to the Lagrangian nature of SPH still needs to be investigated. The orbital velocities at a fix location inside the fluid measured and used in AWAS-v present some numerical noise that leads to instabilities that needs further improvement.

The new functionality of DualSPHysics to generate and absorb waves allows studying 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. Figure 19 represents one of these interesting applications with a floating wave energy converter. Here we can combine the use of a wave-maker with AWAS to absorb reflected waves from the device and a sponge layer is implemented in the end of the tank for passive absorption. In addition, periodic open boundaries

will be used in the lateral walls. In this way a real situation in the open sea can be numerically simulated with DualSPHysics.

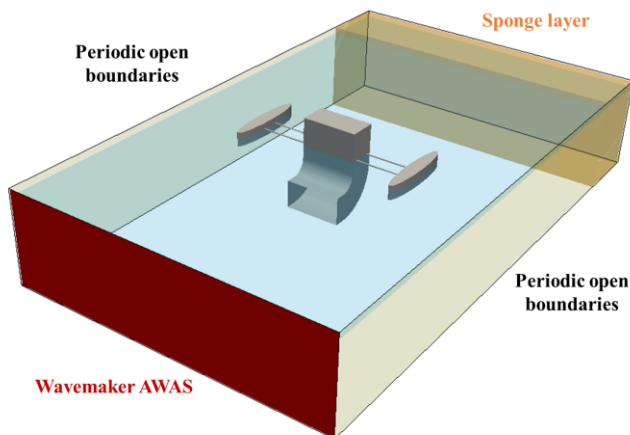


Figure 19. Simulation of floating offshore device with passive and active wave absorption.

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