Coupling between SWASH and SPH for real coastal problems

C. Altomare, T. Suzuki
Flanders Hydraulic Research
Antwerp, Belgium
corrado.altomare@mow.vlaanderen.be,
tomohiro.suzuki@mow.vlaanderen.be

J.M. Dominguez, A.J.C. Crespo
and M. Gómez-Gesteira
EPHYSLAB, Universidade de Vigo
Ourense, Spain
jmdominguez@uvigo.es, alexbexe@uvigo.es,
mggesteira@uvigo.es

***Abstract*—Modelling the whole process of wave propagation, wave transformation and wave-structure interaction is a challenging task both in physical and numerical models. Nevertheless, it is often required for a proper assessment of coastal safety and design of coastal defences. However to study the wave propagation from deep ocean to nearshore is difficult using a single model because multiple scales are present both in time and in space. The present study proposes the use of two different models to generate and propagate the wave field from offshore to nearshore locations. The work aims to develop a technique for the assessment of the action of sea waves on the coast starting from predicted incident wave conditions offshore. Hence a hybrid method has been developed that couples the capabilities of a wave propagation model, SWASH, and a meshfree particle method, DualSPHysics.**

I. Introduction

The latest decades saw a huge development of numerical modelling applied to real life problems. In coastal engineering in particular, the role of numerical models is increasing as essential alternatives or complementary tools to laboratory experiments and prototype measurements. Numerical models are nowadays often used to assess the processes of wave propagation, wave transformation and wave interaction with coastal structures. However outstanding differences exist between the different kinds of models. For instance, grid-based models are widely used in engineering but they are not suitable to represent violent phenomena characterised by large deformations, whereas meshfree models can be still computationally too expensive. In terms of base equations, Boussinesq or nonlinear shallow water equation models have limitations due to the approximation of the governing equations, meanwhile Navier-Stokes based methods can model properly the physics of fluid hydrodynamics but are still characterized by high computational costs. Thereby a single model capable to represent the wave phenomena that occur both offshore and nearshore and to provide accurate results in reasonable computational times is still a challenge nowadays. A different approach can cope with these drawbacks. If the main scope of the modelling is to represent the entire domain from the deep ocean to the nearshore region and to characterise the wave propagation and wave interaction with coastal defences and beaches, the coupling between two different numerical models seems to be a reasonable solution. A coupling, or hybridisation technique, between two models characterized by different capabilities and different computational costs can help to get a complete representation of phenomena at stake.

A hybrid method has been developed starting from the wave propagation model SWASH and the meshfree particle method DualSPHysics. The hybrid model has been validated with physical model data. The purpose is to represent and analyse the transformation of the sea waves due to the processes typical of the surf and swash zones, such as shoaling, wave breaking, uprush and backwash, run-up, etc... A proper representation of the waves nearshore will make possible the proper modelling of the interaction between sea waves and coastal defences (sea dikes, breakwaters, embankments) with a particular focus on the extreme storm conditions propagating from offshore and no-lineal wave transformation.

The so-called SWASH model has been chosen to propagate the sea waves. SWASH is a time domain model for simulating non-hydrostatic, free-surface and rotational flow. Wave propagation models as SWASH have been proven to be able to simulate accurately surface wave and velocity field from deep water and with satisfactory results both at open ocean and nearshore but they are not suitable to deal with abrupt changes of shape of coastal structures.

An SPH-based model has been used to study the wave transformation and breaking at detailed scale close to the shoreline. DualSPHysics [1] is an open-source numerical model based on the Smoothed Particle Hydrodynamics method and can be freely downloaded from www.dual.sphysics.org. The expensive computational cost of SPH in comparison with other meshbased methods for CFD problems can be partially alleviated by general-purpose graphics processing unit (GPGPU) where a graphics processing unit (GPU card) is used to perform computations traditionally managed by big cluster machines with thousands of CPU cores. Thereby DualSPHysics was designed from the outset to use SPH for real engineering problems with software that can be run on either CPUs or GPUs and can simulate millions of particles at a reasonable computation time. Nevertheless, that is not enough when the goal is very demanding like simulating a big domain lasting minutes or even hours (e.g. simulating a real storm).

For all the reasons mentioned above the development of a hybrid model becomes mandatory for coastal applications. The present work describes the implementation and validation phases of a hybrid model. In particular the experimental data from SUSCO project (Hydralab III report, 2010) and SCANDURA project (Hydralab III report, 2009) have been used to validate the goodness of the hybridisation technique.

Previous work using SPHysics code was carried by [2], where a hybrid model was developed combining the main advantages of a Boussinesq model (FUNWAVE) and a SPH model. Numerical models based on the Boussinesq equations are well known to accurately propagate waves from intermediate water depth to nearshore. One of the key developments achieved in this model was the algorithm to prescribe the boundary conditions for the individual models in the overlap region. The boundary conditions for the SPH model were implemented in the form of a Boussinesq wavemaker where a column of SPH boundary particles moves with a velocity determined from the velocity of the adjacent Boussinesq nodes. A simple working case was used to demonstrate the capability of the model to propagate a solitary wave in a constant depth tank. Nevertheless, the study can only be considered a preliminary approach since only a solitary wave was allowed to transit between both subdomains and numerical data were not compared with experiments. In summary, the approach allowed to glimpse the possibility of creating a hybrid model but without checking the capabilities of the approach. In addition, FUNWAVE only provided the velocity at a single height and the rest of the velocities along the water column were calculated from that single value.

II. CASE OF STUDY

Physical model experiments carried out at the Maritime Engineering Laboratory of the Technical University of Catalonia (LIM-CIIRC/UPC) have been used as benchmark case of the hybridisation technique between DualSPHysics and SWASH. The data refer to two EU-funded projects within the Hydralab III framework, namely SUSCO project and SCANDURA project. The tests were conducted in the wave flume so-called CIEM (Canal d'Investigació I Experimentació Marítima). The flume is 100 m long, 3 m wide and 5 m high and has a wedge type paddle that allows generating waves 1.5 m wave high. A sketch of the physical flume from SCANDURA project is shown in Fig. 1: the wedge-type wave generator it can be distinguished on the left side of the figure, where a 1:15 sloping sandy beach represents the initial conditions before erosive and accretive processes triggered by the action of the waves. Similar initial layout characterizes the tests initial configuration of the SUSCO project.

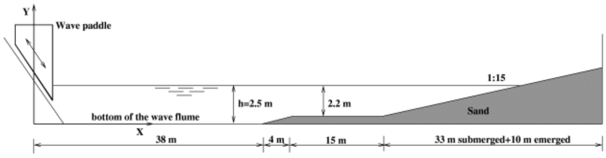

Figure 1. Sketch of the physical flume as in SCANDURA project

Information of water surface elevation and wave particle velocity along the flume and close to the swash zone has been collected during the experimental campaign. Resistance type wave gauges (WG) and acoustic wave gauges (AWG) are normally used to measure the free surface elevation. The WGs measure the current flowing in an immersed probe: the current is proportional to the depth of immersion of the probes with an accuracy of ±1 mm. The AWGs are acoustic sensors that emit ultrasound pulses that are reflected on the measurement object and received back as an echo. The Vectrino Velocimeter (ADV) measures water speed using the Doppler effect by transmitting short pairs of sound pulses, listening to their echoes and, ultimately, measuring the change in pitch or frequency of the returned sound. Their accuracy is about ±0.5% of measured values ±1 mm/s.

III. SWASH MODEL

The SWASH model is a time domain model for simulating non-hydrostatic, free-surface and rotational flow. The governing equations are the shallow water equations including a non-hydrostatic pressure term. The one-dimensional, depth-averaged shallow water equations in non-conservative form are shown as follows:

$$\frac{\partial \zeta}{\partial t}+\frac{\partial hu}{\partial x}=0 \tag{1}$$

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+g\frac{\partial \zeta}{\partial x}+\frac{1}{2}\frac{\partial q_b}{\partial x}+\frac{1}{2}\frac{q_b}{h}\frac{\partial(\zeta-d)}{\partial x}+c_f\frac{u|u|}{h}=\frac{1}{h}\frac{\partial}{\partial x}\left(h\nu_t\frac{\partial u}{\partial x}\right) \tag{2}$$

$$\frac{\partial w_s}{\partial t}=\frac{2q_b}{h}-\frac{\partial w_b}{\partial t}, \quad w_b=-u\frac{\partial d}{\partial x} \tag{3}$$

$$\frac{\partial u}{\partial x}+\frac{w_s-w_b}{h}=0 \tag{4}$$

where t is time, x the horizontal coordinate, u the depth averaged velocity in x-direction, w_s and w_b the velocity in z-direction at the surface and at the bottom, respectively. ζ is the free-surface elevation from still water level, d is the still water depth and h the total depth. q_b is the non-hydrostatic pressure at the bottom, g the gravitational acceleration, c_f the dimensionless bottom friction coefficient and ν_t the eddy viscosity.

A full description of the numerical model, boundary conditions, numerical scheme and applications are given in [3].

IV. Hybridisation Technique

A one-way coupling approach has been selected as a first stage of hybridisation between DualSPHysics and SWASH. The coupling strategy used here is defined as a Moving boundary between SWASH and the SPH domains.

A. Moving boundary

The information of SWASH is passed to SPH domain through a fictitious wall placed between both media: SWASH is run for the whole domain and imposes some boundary conditions on the aforementioned wall. The wall act as a wave paddle in SPH but each particle that forms the paddle will experience a different movement to mimic the effect of the incoming waves (Fig. 2). Note that the wall is not a rigid element but a set of SPH particles that can move and deform at any time step.

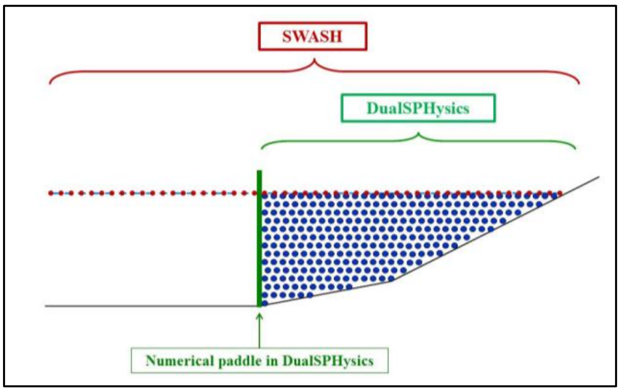

Figure 2. Skecth of the SWASH-SPH hybridization technique

SWASH runs using a multi-layered approach and the time history of the displacement at each point or layer of the propagation model is reconstructed starting from the velocity information and afterwards interpolated along the vertical. The so-calculated movement is passed to the SPH particles that constitute the wave paddle. Thereby the SPH-paddle consists of a set of points whose displacement is imposed by the waves propagated by SWASH and only exists for SPH. The so-built paddle is adjusting is shape every time step basing on the information that is passed by SWASH and interpolated.

B. Piston smoothing

SWASH gives values of velocity in different levels of depth. These values are used to move the piston particles. The displacement of each particle can be calculated using a lineal interpolation of velocity in the *Z* position of the particle. However, the lineal interpolation is not a good option because a small difference in velocity between two piston particles, which are very close in height, gives rise to an important difference in the accumulated displacement after several seconds of simulation. Furthermore, this problem is aggravated further because the height for the velocity measurements can vary at each instant depending on the water height, which can result in a broken piston.

The upper row of Fig. 3 shows how the piston is distorted after 200 and 400 seconds of simulation. The blue line represents the initial level of water and the red box shows the initial position of the piston. The solution is to get a smoothed velocity, in such a way that the difference of velocity between adjacent particles is small compared with the mean velocity. The lower row in Fig. 3 represents the shape of the piston after applying this smoothing technique. The smoothing is based on a sort of weighted average calculated for each particles looking at the information of its neighbour particles (10-20 particles).

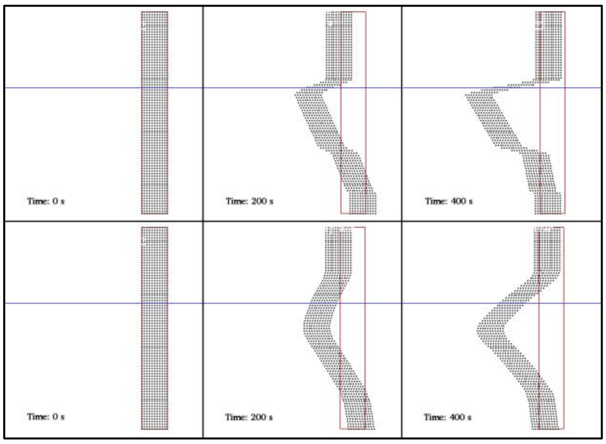

Figure 3. Skecth of the SPH-piston smoothing

V. SWASH Validation

Prior to the hybridisation of the models, the basic behaviour of the SWASH model is compared with experimental results.

Different experiments were carried out within the framework of SUSCO. Here we will only consider the wave conditions and bathymetry used in Test 115 (see Hydralab III report, 2010).

TABLE I. Wave conditions of SUSCO for SWASH validation

Project	**SUSCO**
Test No.	***115***
H [m]	0.370
T [s]	3.7
d [m]	2.5
L [m]	16.1

The bathymetry of test 115 is shown in Fig. 4.

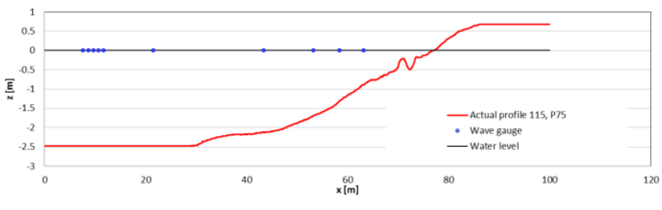

Figure 4. Bathymetry and wave gauge location (Test 115, P75 from SUSCO)

Wave gauges positions are shown in Table II. The horizontal distance x (m) starts from the wave paddle position. Incident waves used in the SWASH simulation are calculated based on the measurement of the time series of water surface offshore. Three wave gauges are used for the incident wave and reflection analysis (e.g. WG0, WG2 and WG3 for test 115). The incident waves are generated at the position of WG0 in the SWASH model: the SWASH computation domain starts at 7.7 m from the wave paddle location of CIEM flume.

TABLE II. WAVE GAUGE LOCATION IN PHYSICAL MODEL (SUSCO)

Wave Gauge		*Actual point*
No.	***WG name***	***X [m]***
1	WG0	7.70
2	WG1	8.72
3	WG2	9.70
4	WG3	10.69
5	WG4	11.69
6	WG5	21.58
7	WG8	43.41
8	WG9	53.28
9	WG13	58.46
10	WG12	63.18

A. *Numerical settings*

Simulations are carried out with SWASH (version 1.10AB) using a grid size of 0.5 m in the horizontal direction with an initial time step of 0.05 s in prototype scale (same scale of physical model). The time series of the incident waves are prescribed at the wave boundary of the SWASH model. The length of the numerical flume is 100 m long with 200 grid cells. Note that the calculation time step is automatically adjusted in the calculation depending on the Courant-Friedrich-Levy (CFL) condition. A maximum CFL value of 0.5 is used. The output time step of the SWASH model is 0.05 s. A weakly-reflective boundary is applied at the wave boundary. A Manning's value of 0.019 is used to calculate the bottom friction, which corresponds to a sandy coast. The time duration of the numerical simulation was 23 minutes, as used in the physical model test. The number of layers tested in the SWASH was 8. Note that the result of wave propagation of 1 layer and 8 layers is not so different since the *kd* (*wave number·water depth*) value is less than 1 in this case. SWASH has been firstly validated for the entire physical domain, showing high accuracy in terms of wave height, wave period and wave setup. An example of the results is shown in Fig. 5: the wave height, wave setup and wave period from SWASH are compared to the physical data. In general a good agreement can be noticed.

Once the model has proven to represent properly the wave propagation toward nearshore areas, the domain has been adjusted to obtain the input for DualSPHysics. In particular a calculation of SWASH with flat bottom and sponge layer behind the coupling point would be suitable for the SPH boundary. In this way, only the properties of the incident wave are transferred from SWASH to SPH (Fig. 6).

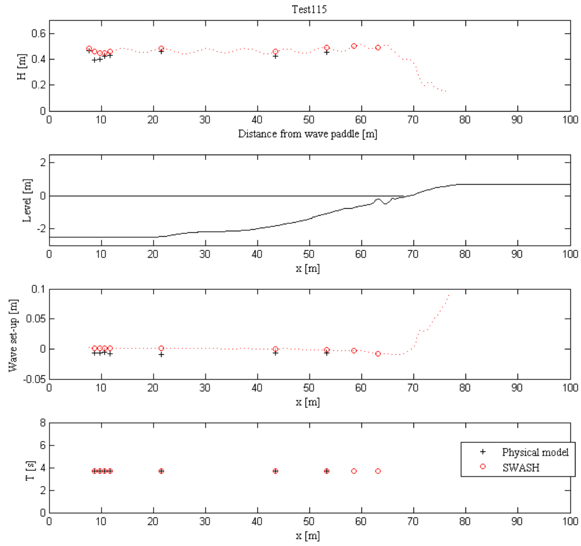

Figure 5. Spatial distribution of wave height, setup and wave period (Test 115, SUSCO)

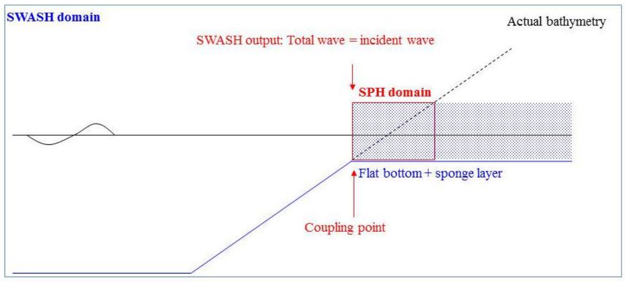

Figure 6. Scheme of the SWASH-SPH hybridisation technique

VI. HYBRIDISATION RESULTS

Test 115 of SUSCO data (Hydralab III report, 2010) and test 63 of SCANDURA (Hydralab III report, 2009) have been used to validate the hybridisation strategy. Those tests have been chosen as former validation cases since their geometry results quite simple (i.e. sandy beach profile): hence the wave reflection is very limited. Furthermore both free surface elevation and particle velocity have been measured along the physical flume, so that a huge amount of data is available for comparison purposes. Only information from wave gauges is used and presented in this work.

Results from SWASH have been used as hydraulic boundary conditions (HBC) in DualSPHysics corresponding to the position of WG8 in the physical model (43.41 m far from the physical wave paddle) for SUSCO. A flat bottom is modelled from WG8 position backwards and the "Moving boundary" in DualSPHysics is finally slightly shifted back to reproduce properly the target wave conditions on horizontal bottom. The wave surface elevation has been measured in the DualSPHysics domain in WG8 and WG9 and compared with the experimental results.

Similarly the WG5 (21.58 m far from the physical wave paddle) has been used as HBC for SCANDURA modelling.

An initial interparticle spacing of 0.02 m has been used to create the SPH particles. The resulting number of fluid particles is around 96,000 for SUSCO and 233,000 for SCANDURA. The physical time simulated is equal to the first 100s of the experiments. The simulation runtimes were respectively about 1.8 and 4.4 hours using an Nvidia GeForce GTX 680 graphic card. The simulation runtime of SWASH was less than 5 minutes. A case with the entire physical domain was also simulated only with DualSPHysics to compare runtimes. The numerical wave paddle mimics the physical one (wedge type) and uses the same time series of displacement. The number of fluid particle is around 356,000 and the computational time about 6.8 hours executed on the same graphics card. The comparison proves that the hybridisation is around 3.7 and 1.5 times less time consuming respectively for SUSCO and SCANDURA with respect to the entire domain case.

Fig. 7 shows a snapshot of the SPH simulation where it is possible to see the of the piston movement (the colours indicate the different velocities of each part of the piston). The input velocities that have been used to calculate the piston displacement in time are plotted in the subfigures where the arrows (c) with different length and colour indicate different velocity along the vertical.

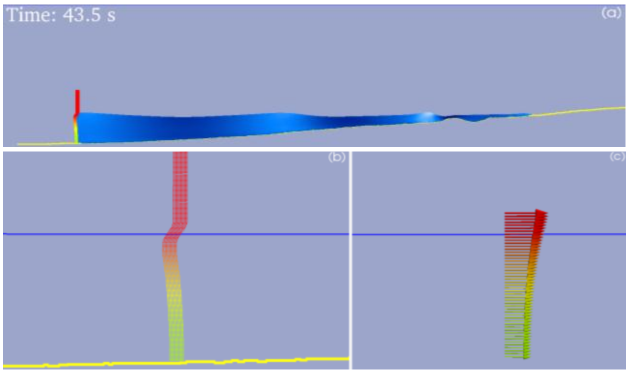

Figure 7. SPH simulation snapshot: (a) entire SPH domain; (b) Piston velocity detail; (c) input velocity from SWASH

Several tests have been performed in DualSPHysics to investigate the sensitivity of the model to parameters related with DualSPHysics and with the piston smoothing. In detail, the attention has been focused on:

a) The relative kernel length *h/dx*;

b) The boundary viscosity: it means that the viscosity considered for the boundary particles has been set equal or not to the fluid viscosity (*v*=0 stays for no viscosity, *v*=1 means application of the same fluid viscosity)

c) The piston smoothing: it identifies the number of neighbour particles to be considered for the smoothing interpolation.

Fig. 8 shows an example of the comparison between numerical and physical results for case Test 63 from SCANDURA project: the wave height, period and wave setup measured by AWGs during the physical experiments are compared with results from only SWASH modelling (labelled as 'SWASH-awg') and from DualSPHysics once coupled with SWASH (labelled as 'SPH'). Good agreement can be noticed, except from the last AWG located at the farthest distance from the wave paddle.

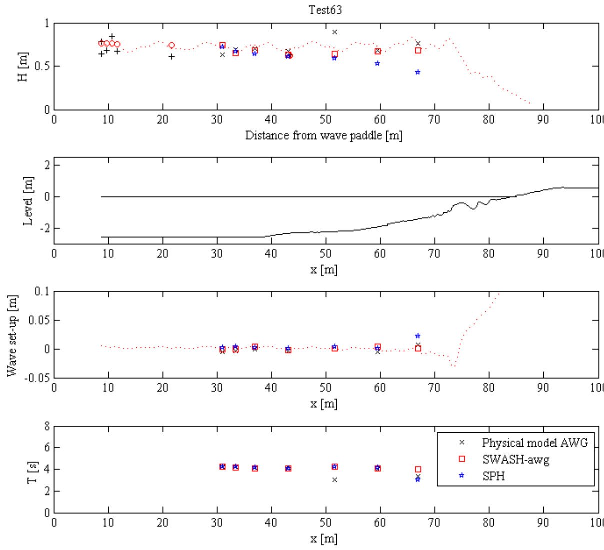

Figure 8. Comparison between numerical and pysical results: spatial distribution of wave height, setup and wave period (Test 63, SCANDURA)

To evaluate the good performance of the coupling technique, the correlation coefficient (R^2) and the Adjusted Relative Mean Absolute error (ARMAE) have been used as error estimators. The ARMAE is defined as follows:

$$\mathrm{ARMAE} = \frac{\langle |Y - X| - \mathrm{OE} \rangle}{\langle |X| \rangle} \qquad (5)$$

where *X* corresponds to the observed values, *Y* to the predicted ones and *OE* is the observational error. Further details about ARMAE can be found in [4] and [5]. Sunderland proposed a classification of the error basing on the ARMAE value (Table III).

TABLE III. ERROR CLASSIFICATION USING ARMAE (SUNDERLAND ET AL. 2004)

Classification	*Range of ARMAE*
Excellent	<0.2
Good	0.2-0.4
Reasonable	0.4-0.7
Poor	0.7-1.0
Bad	>1.0

The time series of the surface elevation from case Test 115 of SUSCO as modelled in DualSPHysics coupled with SWASH (red line) are plotted together with the experimental ones (blue line) in Fig. 9. The black line represents the error calculated as the difference between experiment and hybridisation results). The ARMAE is 0.154 and 0.155 and R^2 is 0.966 and 0.968 respectively for WG8 and WG9. Basing on the classification of [4] the performance results excellent. The ARMAE measured for the case modelling the entire CIEM domain are 0.195 and 0.178 and R^2 is 0.947 and 0.943 respectively for WG8 and WG9. Hence the hybridization between SWASH and DualSPHysics leads to more accurate results than modelling the entire domain only in DualSPHysics.

An example from Test 63 of SCANDURA is also shown in Fig. 10: the free surface elevation measured by 4 AWGs in the physical flume is shown and compared with the numerical results. The resulting ARMAE indicates an excellent or good performance of the modelling.

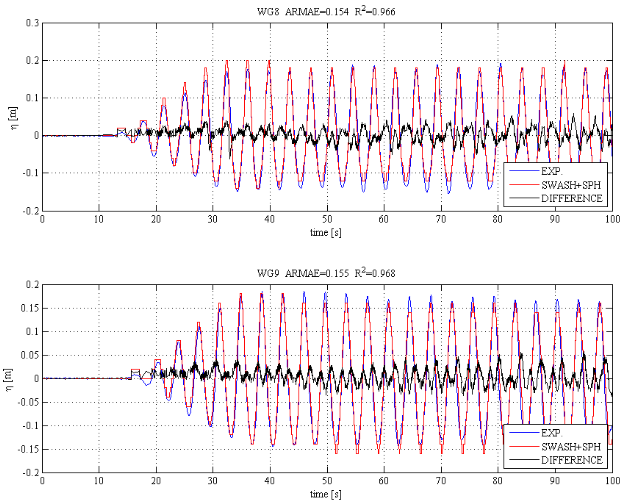

Figure 9. WG free surface elevation: comparison between numerical and phsyical results (Test 115, SUSCO)

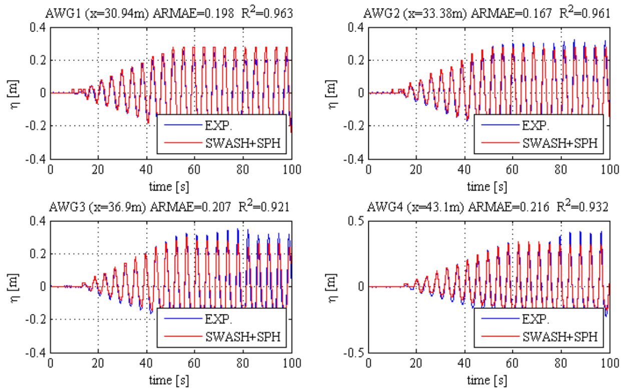

Figure 10. AWG free surface elevation: comparison between numerical and phsyical results (Test 63, SCANDURA)

The coupling strategy can be considered successful since the hybrid model provided more accurate results at a shorter runtime than DualSPHysics.

VII. Conclusions

A hybridisation strategy has been developed between the Eulerian SWASH model (based on the Non Linear Shallow Water equations) and the meshfree particle method DualSPHysics. The hybridisation process is a one-way coupling where the "frozen" information from SWASH is transferred to DualSPHysics in terms of multi-layered velocity time series.

The hybrid model has been validated with physical model data obtained from SUSCO and SCANDURA projects carried out at LIM-UPC.

The results described in the present work represent a first case of application of the new technique. A simple geometry has been chosen in this phase in order to avoid additional complexities making the analysis as simple and reliable as possible.

The Adjusted Relative Mean Absolute Error (ARMAE) has been used to evaluate the performance of the strategy. According to this scale, results can be ranked excellent

Ongoing research also aims to represent irregular waves and finally use the coupling to measure wave impacts on coastal structures.

Acknowledgement

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