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NUMERICAL SIMULATION OF WAVE PROPAGATION OVER A SLOPING BEACH USING A COUPLED RANS-NLSWE MODEL

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1. Introduction

Northern European countries such as Belgium, are characterised by a very typical coastal defence system: a hard dike with a promenade and an almost continuous line of high-rise buildings, fronted by a mildly sloped and very shallow foreshore. The presence of this foreshore influences the wave transformation from offshore to nearshore and the interaction with coastal structures significantly. Its effect is not yet fully understood. Taken into account the role of sea dikes as both coastal defences and recreational spaces, it is essential to fully understand and predict the influence of the foreshore on for example wave overtopping on sea dikes and wave loading forces on buildings. The present research, performed in the framework of the CREST research project [1], aims at developing a reliable and accurate tool for the assessment of wave overtopping over the dike crest and wave loading forces for the specific case of a very shallow foreshore.

2. Numerical framework

Modelling the whole process of wave propagation, transformation, breaking and wave structure interaction is a well-known challenge in the field of coastal engineering.
Non-linear shallow water (NLSW) models are widely used due to its relative simplicity. These models can be applied with good confidence to study wave transformation in the swash zone [2][3] at a limited computational cost. However, depth-averaged models are not exact forms of the governing equations of fluid motion and contain an error of some order [4]. To accurately model the very complex behaviour of the free surface near coastal structures and the associated nonlinear effects, Navier-Stokes (NS) based solvers are required. However, simulating wave propagation and wave transformation over large domains and for long durations with solely a NS solver is currently not feasible due to the requirement of (1) a large computational domain since processes on the beach are driven by waves originally generated at sea and (2) a very high spatial resolution to avoid excessive numerical damping of incoming waves and to accurately simulate wave breaking and wave structure interactions. This results in a very high computational effort.

To obtain the advantages and reduce the disadvantages of both models without loss in accuracy, the authors have investigated a coupling between depth-integrated models and NS models in space. This work describes the simultaneous use of two solvers that belong to the aforementioned categories. The first model which is used, is SWASH [5], a time domain model based on the non-linear shallow water equations. SWASH has proven to accurately reproduce surface elevations for wave transformation over a very shallow foreshore in 1D calculations with very little computational resources due to the depth-averaged assumption and parallel computation capabilities. However SWASH is not able to deal with abrupt changes in geometry e.g. due to the presence of coastal structures [6] and is not suitable to predict in great detail wave loading forces or overtopping volumes over dike crests. The second model which is used, is the CFD model OpenFOAM where the two-phase flow field is resolved by the incompressible Reynolds averaged Navier-Stokes (RANS) equations and the interface is tracked with a volume of fluid method. Contrary to SWASH, OpenFOAM has proven to be able to accurately simulate wave structure interactions [7].

The present coupling methodology is a first straightforward method and consists of a one-way coupling. The NLSW model SWASH is applied in the non-breaking zone and the RANS model OpenFOAM in the zone of high turbulence, breaking waves and wave structure interactions. The two models share a common interface for the data exchange. At this interface, SWASH provides the surface elevation and the velocity values at different levels of depth, depending on the amount of vertical layers used at the coupling location. This information is passed to OpenFOAM and imposed on the inlet OpenFOAM boundary. The coupling interface is located at a low turbulence area. More details about the coupling methodology will be presented at the workshop.

3. Results & Discussion

To test the model for validity, the coupled model is used to simulate two scenarios: (1) solitary wave propagation in a flume with constant water depth and (2) solitary wave propagation over a sloping beach.

In the first case the propagation of a solitary wave with an amplitude of 0.05 *m* in a 28.0 *m* long channel with a constant water depth of 0.5 *m* is simulated. The domain is divided in two subdomains: a subdomain with a length of 18.0 *m* occupied by the NLSW model and a subdomain of 10 *m* occupied by the RANS model. The wave is generated in the NLSW domain and propagates to the RANS model domain.

The evolution of the solitary wave as it propagates along the channel can be seen in Figure 1 (solid blue line) where several snapshots of the free surface elevations at different times are presented. The results clearly demonstrate that the solitary wave maintains its original shape and the wave height does not vary when propagating through the channel. The wave is correctly transmitted from the NLSW to the RANS domain, no disturbance takes place at the coupling interface located at x = 18 *m*. For comparison the simulation is also performed with the NLSW model in the complete domain. These results are shown with red dots. There is good agreement between the NLSW standalone results and the coupled model results. Figure 2 shows a snapshot of the entire computational domain modelled with the coupled model. In the left part, only the free surface calculated with SWASH is shown, the right part depicts the results obtained with OpenFOAM, where the colours represent the horizontal velocities. The coupled model saves computational time by a factor proportional to the reduction in cells in the OpenFOAM model.

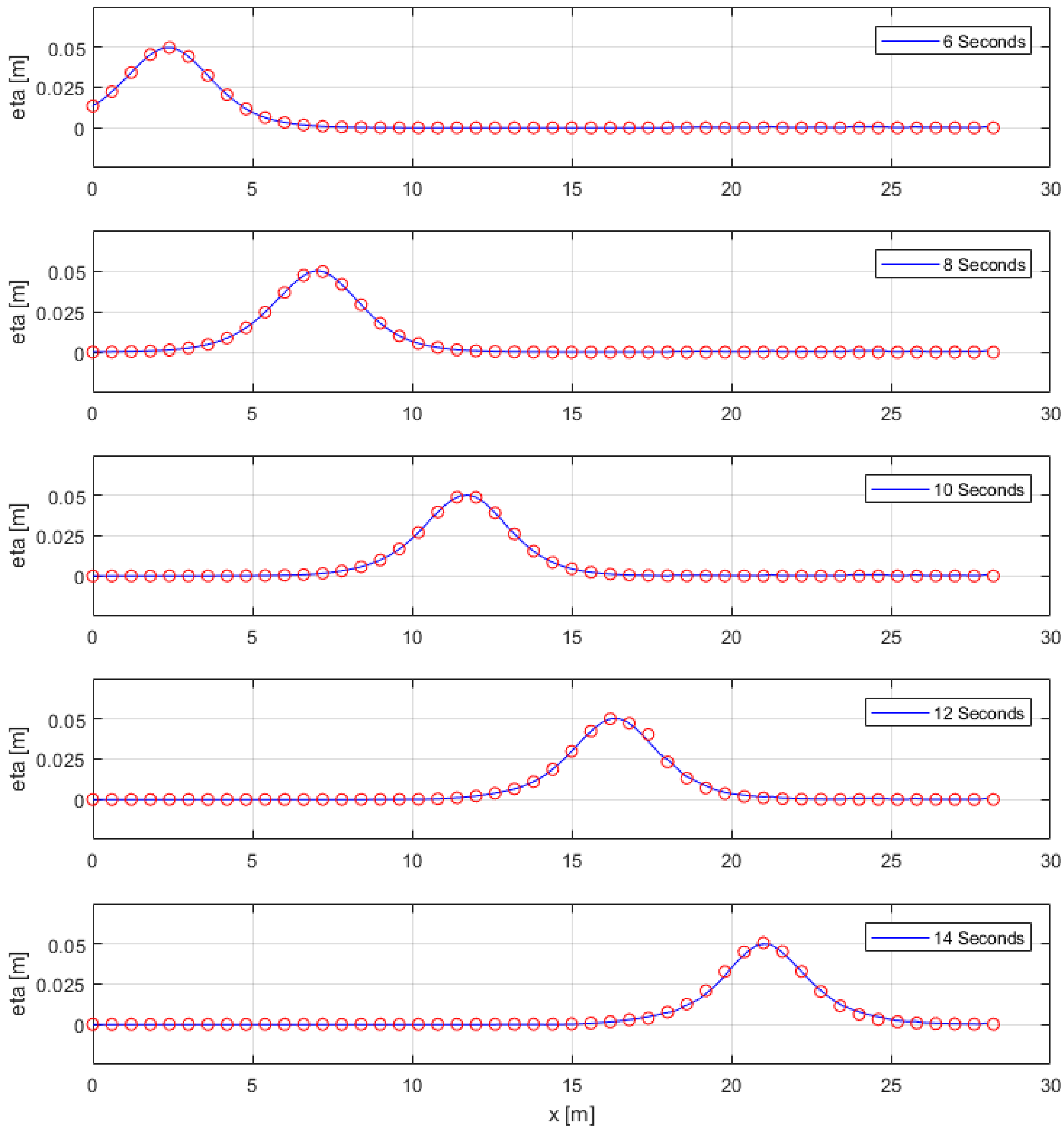

Figure 1: Surface elevation for solitary wave propagation over a flat bottom. Dots represent the results of a SWASH stand-alone simulation over the complete domain. The blue line represents the results of the coupled model (0 *m* ≤x≤ 18 *m*: SWASH, 18 *m* ≤x≤ 28 *m*: OpenFOAM).

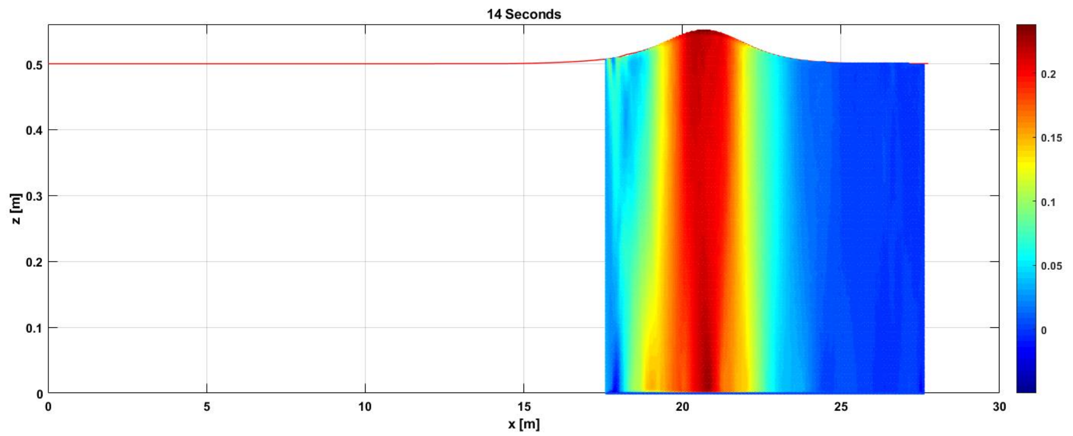

Figure 2: Snapshot of the simulation for the entire domain modelled with the coupled SWASH-OpenFOAM model. The colours represent the horizontal velocity.

A second test case simulates the propagation of a solitary wave over a sloping bottom similar to the experiment of Zelt [8]. A sketch of the simulated case is depicted in the upper corner of Figure 3. The wave is generated in the NLSW domain and propagates to the RANS model domain, respectively with a length of 10.0 *m* and 5.0 *m*. The wave gauge is located at a distance 7.87*d* from the toe of the foreshore with *d* the water depth conform the experimental test. The coupling location is chosen on the horizontal part of the bottom, 0.05 *m* before the wave gauge.
The time series of the surface elevation normalised with the water depth *d* at the indicated wave gauge is also shown in Figure 3. The numerical results are represented by the solid blue line. Experimental data are marked with red dots. The first peak corresponds to the incident wave, the second to the reflected wave. A good agreement is found both for the incident and the reflected wave between the experimental data and the obtained numerical results.

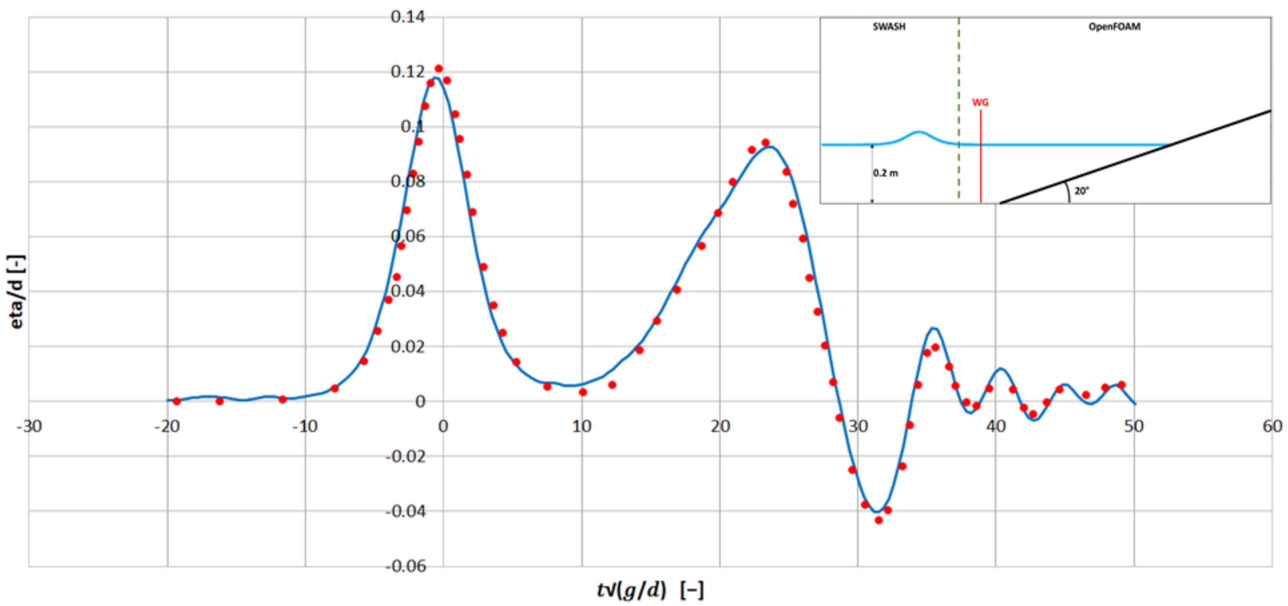

Figure 3: Normalised surface elevations at the indicated wave gauge (WG) for the case of wave propagation of a solitary wave over a sloping beach. The red dots represent experimental data of Zelt [8]. The solid blue line represents the results of the coupled numerical model.

4. Conclusions

A coupled model is developed starting from the NLSW model SWASH and the NS model OpenFOAM. The presented approach is a one-way coupling. The aim of this coupled model is to achieve the same accuracy with the coupled model as with a full RANS solution but reducing considerably the computational time.
The obtained results demonstrate the capabilities of the coupled model to generate and propagate waves. Future work will include further development of the model and the application of the model to cases with very shallow foreshores. The proposed method shows great promise to allow a realistic prediction of wave overtopping and wave loading forces with reasonable computation cost in the future.

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