ADVANCEMENT OF NUMERICAL WAVE MODELLING FOR COASTAL ENGINEERING APPLICATIONS

by

Vincent GRUWEZ[1], **Maximilian STREICHER**[1], **Panagiotis VASARMIDIS**[1],

Vicky STRATIGAKI[1,2] and **Peter TROCH**[1]

[1] Department of Civil Engineering, Ghent University, Belgium

[2] Jan De Nul, Aalst, Belgium

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1 INTRODUCTION

Low-lying countries typically have mildly-sloping beaches as part of their coastal defence system. For countries in north-western Europe high-rise buildings are a common sight close to the coastline. They are usually fronted by a low-crested sea dyke with a relatively short promenade, where the long (nourished) beach in front of it acts as a very/extremely shallow foreshore as defined by Hofland et al. (2017). Along the cross section of this hybrid beach-dyke coastal defence system, storm waves are forced to undergo many transformation processes before they finally hit the buildings on top of the dyke. These hydrodynamic processes include: shoaling, sea and swell wave energy transfer to sub- and superharmonics via nonlinear wave-wave interactions, wave dissipation by breaking and bottom friction, reflection against the dyke, wave run-up and overtopping on the dyke, bore impact on a wall or building, and finally reflection back towards the sea interacting with incoming bores on the promenade.

For the design of storm walls or buildings on such coastal dykes, the wave impact force expected for certain design conditions needs to be estimated. Due to the complexity of the processes involved, usually physical modelling is applied, but numerical modelling of these combined processes has become feasible during the last decade. This paper investigates which type of numerical model is practically applicable for this case. Three open-source CFD models are selected, each representing one of the most popular in its category: (1) a Reynolds-Averaged Navier-Stokes (RANS) model (OpenFOAM®, abbr. 'OF'), (2) a weakly compressible Smoothed Particle Hydrodynamics (SPH) model (DualSPHysics, abbrev. 'DSPH'), and (3) a non-hydrostatic NonLinear Shallow Water (NLSW) equations model ('SWASH'). They are validated and compared to large-scale experiments of overtopped wave impacts on coastal dykes with a very shallow foreshore and their model performance is evaluated.

The correct simulation of the waves in the nearshore zone requires the accurate modelling of all the processes involved, such as the generation of the waves, their propagation, transformation and reflection or absorption at the domain boundaries. In this paper, a new wave generation method is also examined for the non-hydrostatic wave model, SWASH, to avoid reflections at the location of the wave generation boundary. The new method is compared and evaluated against other wave generation methods for the practical application of waves diffracting around a breakwater.

2 LARGE-SCALE PHYSICAL MODELLING

The large-scale hydraulic experiments [Streicher et al., 2017] were performed in the Deltares Delta Flume (L x W x H: 291.0 m x 5.0 m x 9.5 m) and the model geometry was built at Froude length scale 1-to-4.3. The moveable sandy foreshore had a transition slope of 1:10 and a slope of 1:35 up to the toe of the dyke (Figure 1). The smooth impermeable concrete dike had a slope of 1:2 and a promenade width of 2.35 m. The promenade had an approximate inclination of 1:100 in order to help drain the water after an overtopping event. At the end of the promenade a 1.6 m high wall was built which covered the entire flume width. Measurements included (but not limited to): 1) free surface elevations η along the length of the flume, 2) overtopping flow layer thickness and horizontal velocity U_x on the promenade, 3) overtopping wave impact pressures p and horizontal force F_x on the vertical wall. Both bichromatic and irregular waves were included in the test matrix. The obtained data-set is available open source [Kortenhaus et al., 2019] and is, besides others, used for numerical model validation purposes.

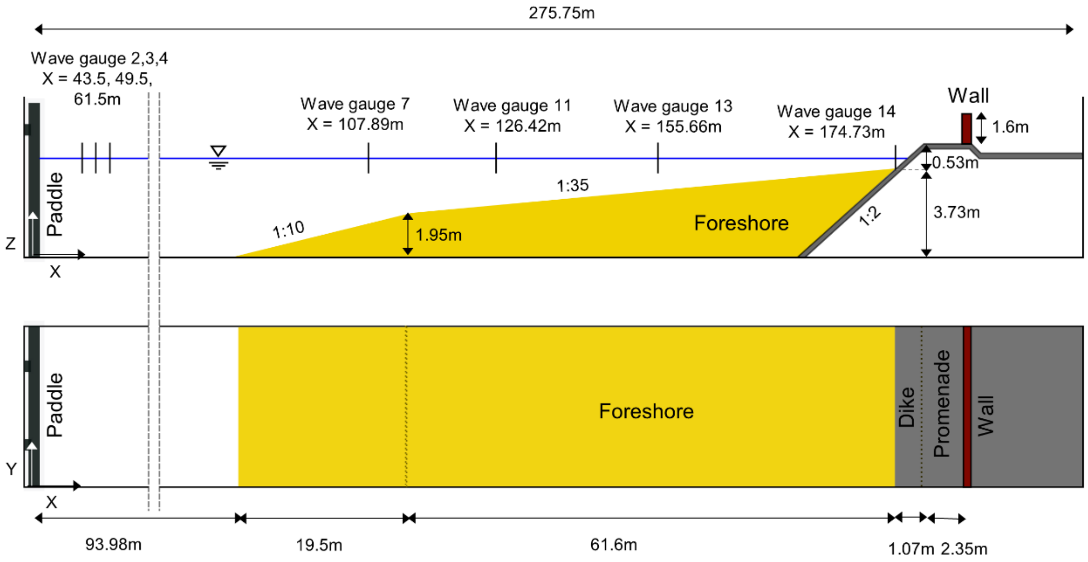

Figure 6: Overview of the geometrical parameters of the wave flume and WALOWA model set-up, with indicated wave gauge locations

Bichromatic wave tests are selected from the experiments for the numerical model validation and comparison, because of their short duration (limits computational cost and a fixed bottom foreshore assumption becomes acceptable).

3 VALIDATION OF OPENFOAM

A RANS multiphase solver for two incompressible and immiscible fluids (water and air), interFoam of OpenFOAM® with olaFlow wave boundary conditions (OF), was applied in 2DV for bichromatic wave transformations over a cross-section of a hybrid beach-dike coastal defence system, consisting of a steep-sloped dyke with a mildly-sloped and very shallow foreshore (Figure 1), and finally wave impact on a vertical wall. OF was validated for the first time in this context [Gruwez et al., 2020a], where – prior to impact – waves undergo many nonlinear transformations and interact with a dyke slope and promenade. A large-scale experiment (EXP) of bichromatic waves and its repetition (REXP) were selected for this validation. The repeated test allowed to assess the accuracy of the measurements, uncertainty due to model effects and variability due to stochastic processes in the experiment.

After a convergence analysis of the most important numerical parameters (i.e. grid resolution and CFL number), and without calibration of the numerical model, a very good qualitative comparison with EXP was achieved by OF (Figure 2), confirmed by a quantitative model performance rating of Very Good compared to the experiment for all relevant design parameters (i.e. η, U_x, p and F_x), which demonstrates

OF’s applicability for the design of such hybrid coastal defence systems. Remaining discrepancies were found to be mainly caused by the different wave generation methods applied in OF (static boundary) and EXP (moving wave paddle), which caused an underestimation of the incident wave energy and an overestimation of the wave setup in OF compared to EXP. Consequently, when applying OF for a design of a hybrid coastal defence system, the incident wave energy is recommended to be calibrated, while the wave setup development for a static boundary condition with active wave absorption in OF is actually closer to the field condition compared to EXP (finite water mass).

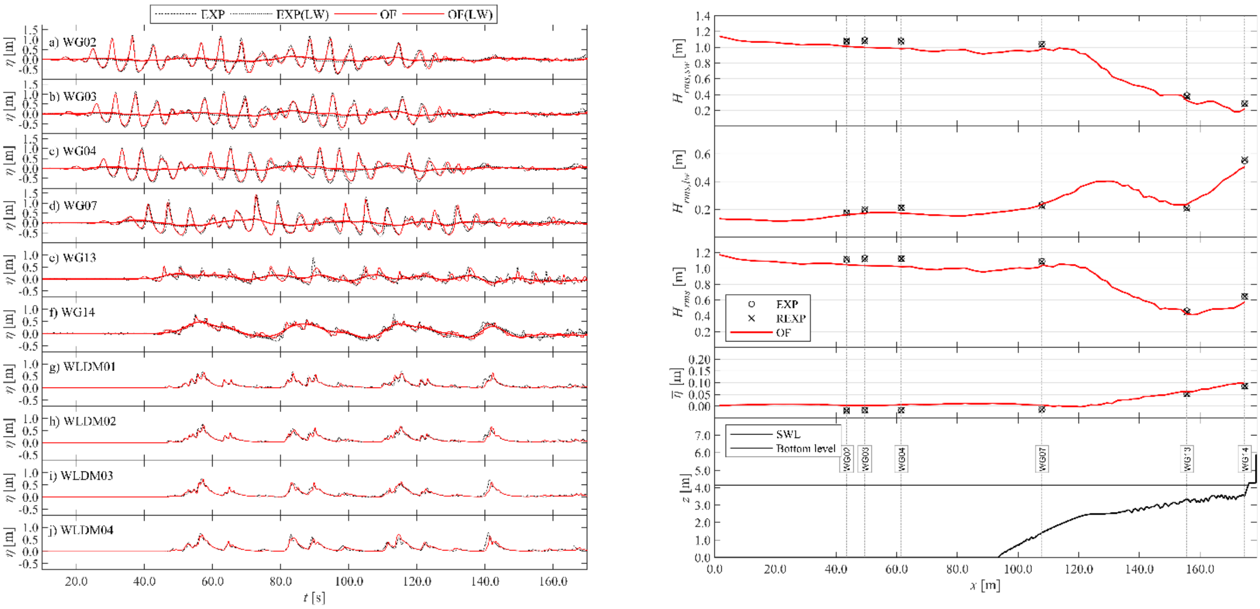

*Figure 7: Left: Comparison of the η time series at all sensor locations, including the long wave η_{LW} in (**a**) – (**f**) (bold lines). The zero-reference is the SWL for (**a**) – (**d**) and the promenade bottom at the sensor location for (**e**) – (**h**). Right: Comparison of H_{rms} between OF and (R)EXP up to the dyke toe. From top to bottom: $H_{rms,sw}$ for the short wave components, $H_{rms,lw}$ for the long wave components, H_{rms} for the total η, the wave setup $\bar{\eta}$ and finally an overview of the sensor locations, SWL and bottom profile.*

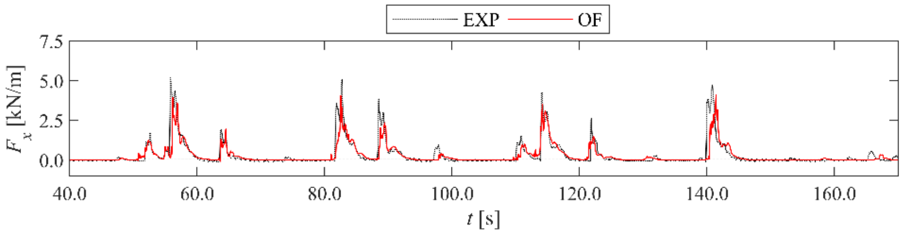

Figure 8: Comparison of F_x time series at the vertical wall between the physical (EXP) and numerical (OF) model.

A detailed comparison of snapshots at key time instants of bore interactions (Figure 4) leading up to the first bore impact on the vertical wall (i.e., *t* = 56s in Figure 3), revealed that very good pressure profiles along the vertical wall are reproduced by OF when the bore interaction patterns on the promenade are reproduced accurately.

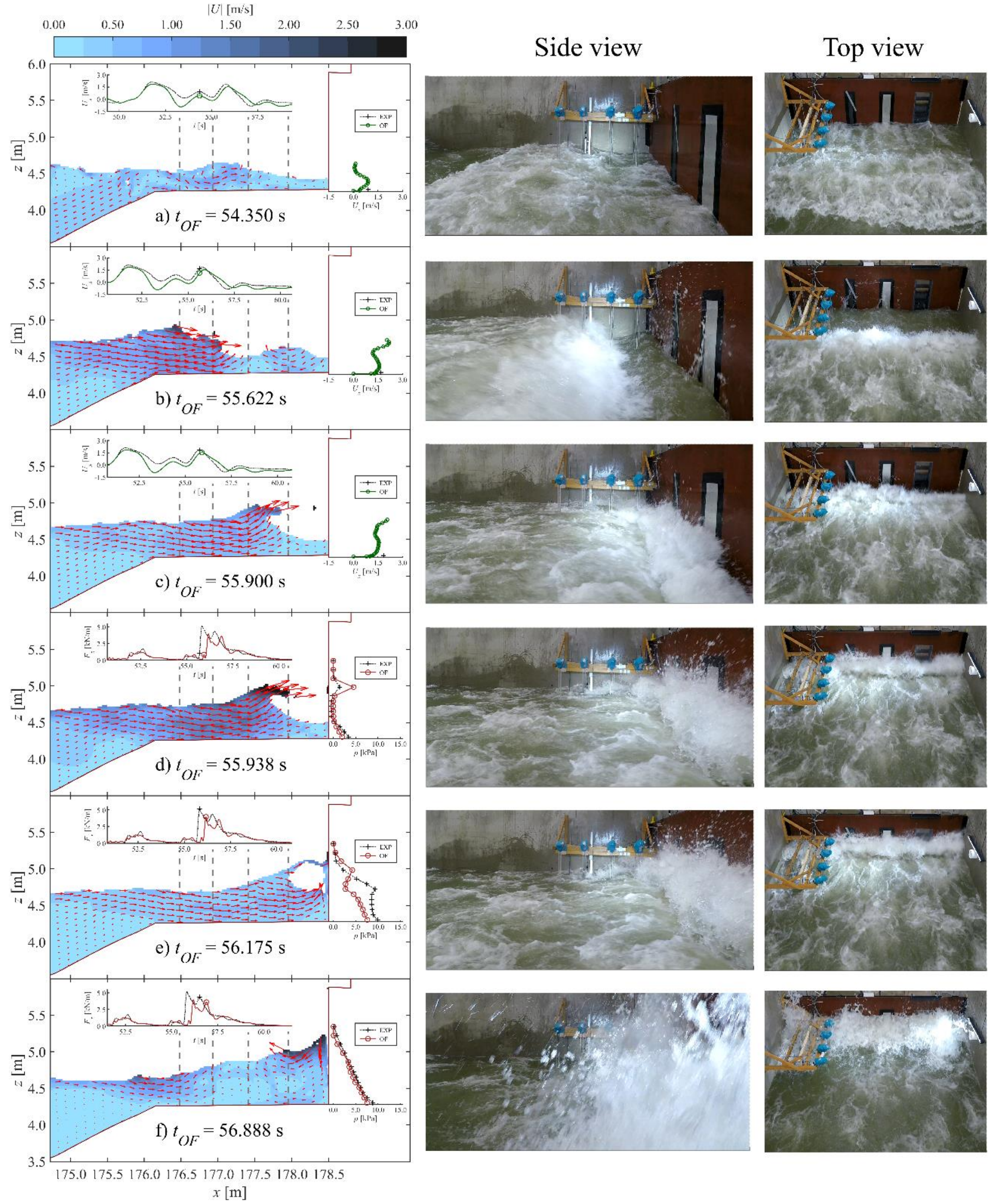

*Figure 9: Snapshots of selected key time instants chronologically over the first main impact (a-f). The OF snapshot (left) is compared to the equivalent EXP snapshot from the side view (centre) and top view (right) cameras. In the OF snapshots, the colours of the water flow indicate the velocity magnitude |U| according to the colour scale shown at the top. The red arrows are the velocity vectors, which are scaled for a clear visualisation. Each OF snapshot has two inset graphs: at the top is a time series plot of U_x (for EXP and $\overline{U_x}$ for OF) (**a-c**) or F_x (**d-f**), in which a circle marker (o) and a plus marker (+) indicate the time instant of the numerical and experimental snapshot respectively. Along the vertical wall U_x (**a-c**) or p (**d-f**) is plotted at respectively the ECM sensor location or each PS location (the vertical axis is z [m]). Along the promenade four vertical grey dashed lines indicate the sensor locations on the promenade, of which the layer thickness gauges are also visible in the experimental snapshots (topped by blue plastic bags). The location of the current velocity meter is at the second vertical grey dashed line from the left. The time instant of the numerical snapshot is provided by t_{OF}.*

4 INTER-MODEL COMPARISON

Next, OF was also compared to two other prominent open source computational fluid dynamics (CFD) numerical models [Gruwez et al., 2020b]: (1) the weakly compressible SPH model DualSPHysics (DSPH) and (2) the non-hydrostatic NLSW equations model SWASH (depth-averaged (K = 1): SW1L, and multi-layered (K = 8): SW8L). The inter-model comparison of those three numerical models to the experiment (EXP) demonstrated that they are all capable of modelling the dominant wave transformation (i.e. propagation, shoaling, wave breaking, energy transfer from the SW components to the bound LW via nonlinear wave-wave interactions) and the wave-structure interaction (i.e. individual wave overtopping, bore interactions, and reflection processes) processes involved leading up to the impacts on the vertical wall, albeit with a varying degree of accuracy. Based on a qualitative time series comparison, all three applied numerical models initially appeared to have a good correspondence of η, U_x, p and F_x to EXP. In the quantitative analysis, none of the numerical models managed to achieve an ideal model performance, but still a rating of Good to Very Good was achieved by all three of them for most parameters and measured locations. The best overall model performance was achieved by OF, but required the highest computational cost. Although DPSH managed the best reproduction of the wave height until the dike toe, accumulation of errors in the wave setup and wave phase in the surf zone and near the dyke toe, caused a lower model performance than OF at the dyke toe and for the processes on the dyke. From this followed that accurate modelling of the wave setup and wave phases at the dyke toe seem to be most important for accurate modelling of the bore interactions on the promenade.

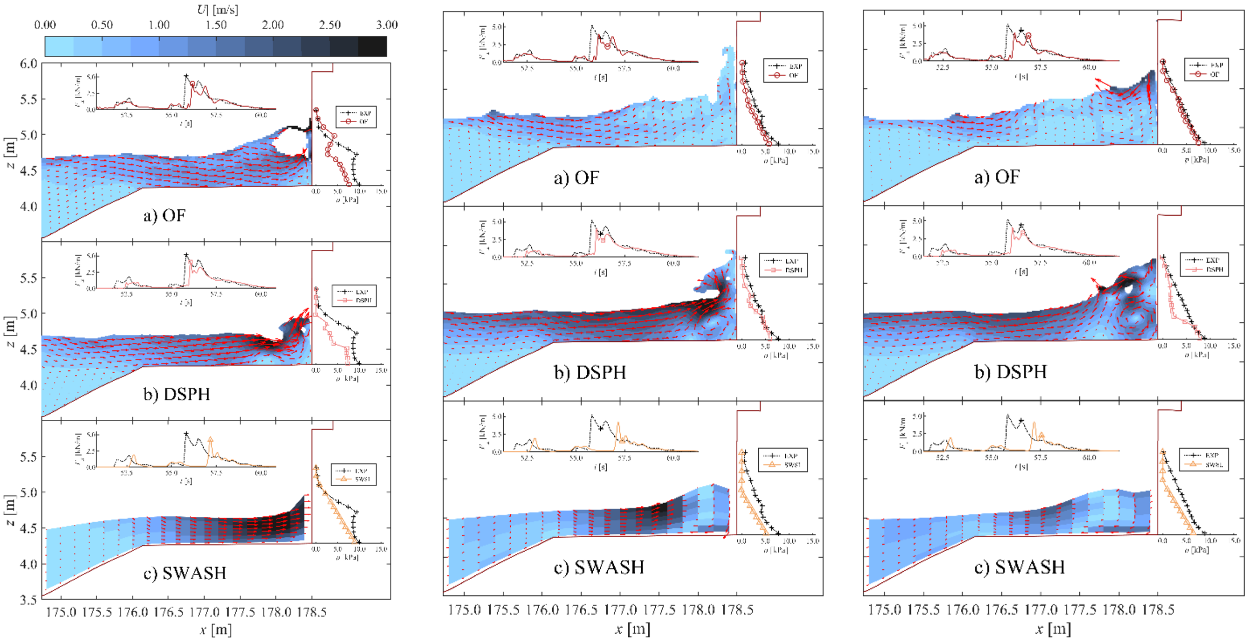

Figure 10: Snapshots of numerical model results on the dyke for three key time instants (red arrows are U vectors).

An analysis and comparison of snapshots of the numerical results on the dike (Figure 5) revealed that these bore interactions are determinative for an accurate reproduction of the impacts on the vertical wall. Even though SWASH is a much more simplified model than both OF and DSPH, it is shown to provide very similar results, even for some of the more complex processes on the dike and impacts on the vertical wall. When the impulse of the force on the structure is of lesser importance, SWASH is still able to predict $F_{x,max}$ relatively accurate for each individual impact, with a significantly reduced computational cost, compared to OF and DSPH. However, SWASH is limited to hydrostatic pressure profiles for the impacts on the vertical wall, which is not always valid during more dynamic impact events (Figure 5c, left).

5 IMPROVED WAVE GENERATION IN SWASH

There are three main methods to generate waves in numerical models. Method 1: weakly reflective wave generation (static boundary), method 2: moving boundary wave generation, and method 3: internal wave generation. In methods 1 and 2, in order to avoid reflections in front of the wave generator, a boundary condition is applied at the same location, according to which the total velocity is a linear superposition of the velocity of the target waves and the velocity of the waves propagating towards the boundary. This condition is making use of the assumption that the waves propagating towards the boundary of the computational domain are shallow water waves with small amplitude and direction perpendicular to the domain boundary and thus, these methods are considered weakly reflective when dispersive and directional waves are examined. To avoid this limitation, a new internal wave generation method has been developed for the non-hydrostatic wave model, SWASH. According to this method, waves are generated internally over an area called the 'source area', while sponge layers (relaxation zones) are used at the domain boundaries to absorb the incoming waves [Vasarmidis et al., 2019].

To verify the added value of the new internal wave generation (method 3) in comparison with the weakly reflective wave generation boundary (method 1), simulations were conducted for irregular short-crested waves diffracting around a breakwater (impermeable vertical wall). In this way, the two different wave generation methods were evaluated against a benchmark experimental test case where oblique dispersive waves propagate back towards the generation area [Vasarmidis et al., 2021]. In Figure 11, a three-dimensional visualisation of the short-crested waves diffracting around the vertical wall is presented using the internal wave generation. The diffraction patterns at the lee side of the wall as well as the increase of the wave amplitude due to the reflection in front of the wall are clearly visible. Figure 12 presents a comparison between the performance of the two wave generation methods for predicting the diffraction coefficients at the lee side of the wall for two cases of irregular waves with narrow (N1) and broad (B2) directional spreading. It can be observed that the error for method 1 is at least double than the one corresponding to the new implemented method 3.

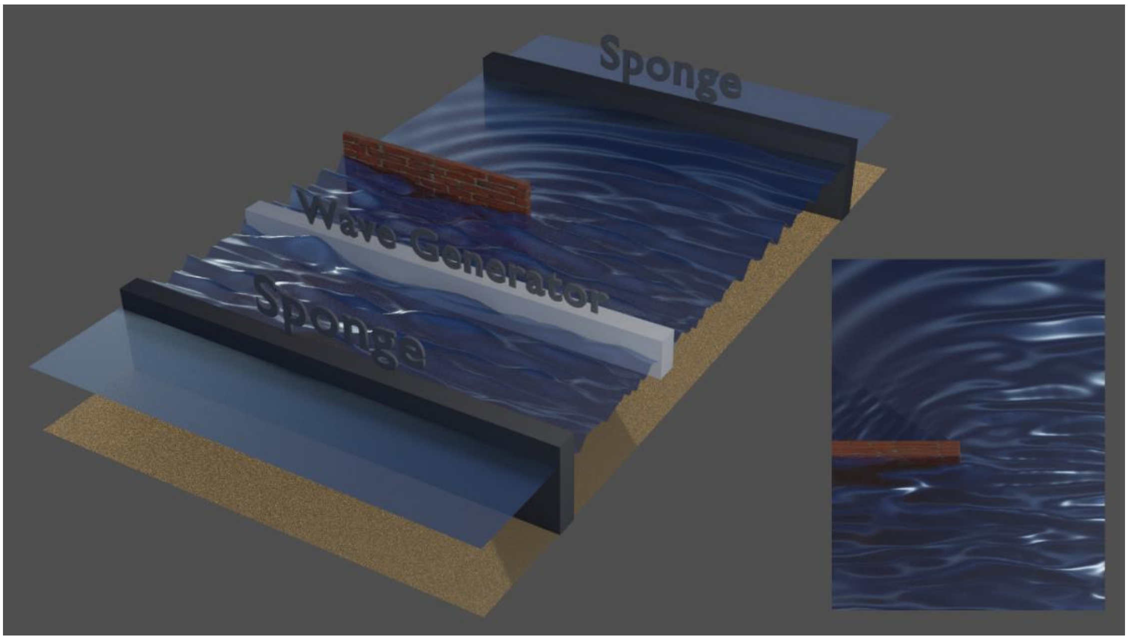

Figure 11: 3-D visualisation of short-crested waves diffracting around a vertical wall as calculated with SWASH using the newly implemented wave generation method 3.

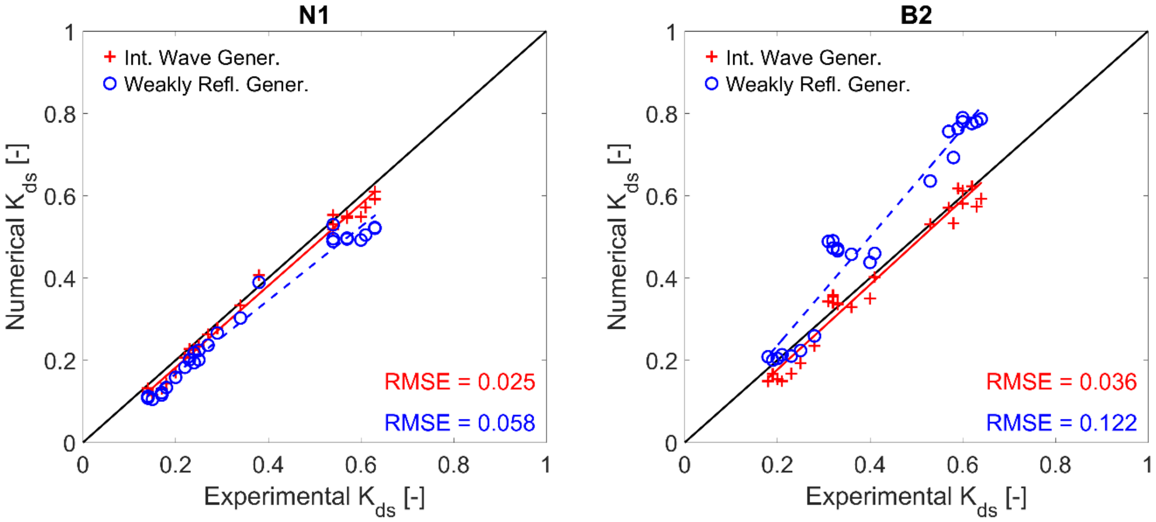

Figure 12: Comparison between the performance of the internal wave generation (method 3, red plus signs) and the weakly reflective generation (method 1, blue circles) for predicting the diffraction coefficients for narrow (N1) and broad (B2) directional spreading

6 CONCLUSIONS

OpenFOAM was successfully validated for the first time for wave transformations over and wave-interactions with a dike on a shallow foreshore, using high-quality large-scale physical modelling data. An inter-model comparison with DualSPHysics and SWASH further showed that OF is most accurate, but requires the longest calculation time. SWASH is by far the fastest model, and can still provide similar results in terms of wave transformations and maximum impact forces, but only for quasi-static impacts and when the force impulse is not important. Finally, it has been proven that the new internal wave generation method increases the capability of SWASH towards the study of wave propagation of highly dispersive short-crested waves in coastal environments with minimal reflection from the boundaries, thereby increasing the accuracy of the generated wave field for practical applications beyond the state-of-the-art. This study has therefore advanced numerical wave modelling in important ways for coastal engineering applications.

7 ACKNOWLEDGEMENTS

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SUMMARY

Over the last decades, numerical wave modelling is increasingly used as an additional tool that is complementary to physical modelling in the design and research of waves interacting with coastal structures. Accurate wave generation and thorough validation of these numerical wave models are crucial first steps in that process. Three prominent open source computational fluid dynamics (CFD) numerical models – OpenFOAM®, DualSPHysics and SWASH – are compared and successfully validated to large-scale physical model experiments in the Deltares Delta Flume (the WALOWA project) of waves interacting with a dike on a shallow foreshore (the typical geometry of e.g. the Belgian coastal defence system against flooding). In addition, a new wave generation method is implemented in SWASH to increase the accuracy of the generated wave field for practical applications beyond the state-of-the-art.

RESUME

Au cours des dernières décennies, la modélisation numérique des vagues est de plus en plus utilisée comme un outil complémentaire à la modélisation physique dans la conception et la recherche des vagues interagissant avec les structures côtières. La génération précise de vagues et la validation approfondie de ces modèles numériques de vagues sont les premières étapes cruciales de ce processus. Trois modèles numériques de dynamique des fluides numériques (CFD) à source ouverte – OpenFOAM®, DualSPHysics et SWASH – sont comparés et validés avec succès par rapport à des expériences de modèles physiques à grande échelle dans le Delta Flume de Deltares (le projet WALOWA) de vagues interagissant avec une digue sur un estran peu profond (la géométrie typique, par exemple, du système de défense côtière belge contre les inondations). En outre, une nouvelle méthode de génération de vagues est mise en œuvre dans SWASH afin d'augmenter la précision du champ de vagues généré pour des applications pratiques au-delà de l'état de l'art.