NON-HYDROSTATIC WAVE MODELLING IN PARTLY SHELTERED AREAS

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The determination of wave conditions in partly sheltered areas is a challenging task for coastal engineers. Knowledge about these conditions is important for the design of coastal structures, the planning and operation of ports. Numerical models play an important role in the assessment of these conditions. Various types of models have been proposed of which phase averaged and phase resolving models are the most widely used. Here, we present the non-hydrostatic phase resolving SWASH model as a tool to determine wave conditions in partly sheltered areas. Examples are shown of wave diffraction behind a semi-infinite breakwater, and the penetration of waves into the harbour of Limassol, Cyprus. The computational results show good agreement with theoretical and experimental results, indicating that the SWASH model can be used as a tool to determine wave conditions in partly sheltered areas.

Keywords: wave modelling; wave penetration; SWASH; wave reflection, wave diffraction

INTRODUCTION

The amount of wave penetration into partly sheltered areas, like harbour basins, is an essential parameter in e.g., the design of coastal defence structures, revetments, the determination of mooring forces and workability conditions in ports. The layout of the harbour basin, the entrance channel and its protecting breakwaters are factors that influence the amount of wave penetration for given design wave conditions. Optimizing these factors may lead to significant cost savings in the building and maintenance of coastal ports. As physical model experiments are rather costly to investigate the consequences of various layouts, coastal engineers rely more on the use of numerical wave models. As each numerical model is based on approximations of the relevant physical processes, the applicability of the model needs to be tested against theoretical results and physical model experiments. Such a validation is the topic of this paper, in which we test the applicability of the non-hydrostatic phase resolving SWASH model to determine the wave penetration to the port of Limassol, Cyprus.

Waves entering a partly sheltered area have usually been generated on the open ocean, where wave generation by wind, dissipation by white-capping and non-linear four-wave interactions are the dominant processes. As the waves propagate to coastal areas, shallow water processes like bottom friction, depth-induced breaking, mud damping and refraction start to play an additional role (see also Salmon et al., 2014). When the waves reach the port, also (partial) reflection and transmission against breakwaters and quay walls need to be taken into account, while diffraction becomes important in the sheltered areas. The modelling of wave evolution from the ocean to the port can best be achieved by a chain of models, each focusing on a particular aspect of the wave field. On the open ocean, an explicit time-stepping third-generation spectral model like Wavewatch III (Tolman., 1991, 2009) is most suited, whereas in the coastal zone the implicit third-generation model SWAN (Booij et al., 1999, SWAN Team, 2014) is an adequate tool. In complex harbour environments, however, those phase-averaged models may be less suited as they do not contain diffraction effects. Instead, phase-resolving time domain models may be needed to accurately resolve these effects. Diffraction effects do not only occur behind breakwaters protecting a harbour, they may also play a role in the wave-entrance channel interaction (Misra et al., 2007; Dusseljee et al., 2014). Commonly used phase resolving models include mild-slope models (Berkhoff, 1972), Boussinesq type wave models (Madsen and Sørensen, 1992) and non-hydrostatic wave-flow models (Zijlema et al., 2011). These models predict the transformation of the free surface elevation in areas with a varying depth and partial reflections against quay walls. In this paper, we present results of the application of the non-hydrostatic flow model SWASH of Delft University of Technology (Zijlema et al., 2011) to compute the wave penetration into partly sheltered areas.

To assess the applicability of the SWASH model for solving coastal engineering problems, validation tests need to be carried out that critically examine the performance of the model. For simple cases, like the penetration behind semi-infinite breakwaters, analytical solutions are available (cf. Goda et al., 1978). However, for more complicated areas like harbours, experimental validation material is scarce and often not fully suited for model testing. One of the first tests of the applicability of SWASH

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for harbour applications was carried out by Alabart et al. (2014) who achieved acceptable results. Here, we present a comparison model experiments carried out by Delft Hydraulics (now Deltares) for the port of Limassol (Dekker, 1991). Although the available model data only consist of measured values for the significant wave height and peak period, and for only one condition, they prove to be valuable for our purpose. It is noted that the Limassol test data were also used by Reijmerink (2012) and Adytia (2014) for similar purposes.

THE SWASH MODEL

The SWASH (Simulating Waves till Shore) is a non-hydrostatic wave-flow model for deep and shallow water (Zijlema et al., 2011). It is based on the non-linear shallow water (NLSW) equations and is applicable to all spatial and temporal scales. NLSW-type models like SWASH conserve mass and momentum. A key component of such models is the inclusion of the non-hydrostatic pressure allowing the modelling of many other phenomena like non-linear triad and quadruplet wave-wave interactions, dispersion, surf beat, wave breaking (Smit et al., 2013), rip-currents and turbulence structure (Zijlema, 2014). By dividing the water depth into a number of vertical layers, the vertical structure of the flow can be resolved, thereby improving the dispersion characteristics of wave propagation. The numerical implementation of SWASH is based on an explicit, second order accurate (in space and time) finite difference method that conserves both mass and momentum at the numerical level (Zijlema et al. 2011, Smit et al., 2013). The computational grid is either rectilinear or curvilinear one, and is vertically discretized with a fixed number of layers of equal thickness between the fixed but spatially varying bottom and the moving, free surface. A staggered grid arrangement is employed for the coupling between velocity and pressure to prevent checkerboard oscillation. Another attractive feature of SWASH is that it can be run in parallel mode making its in large domains feasible.

The SWASH model has some distinctive features that make it more generally applicable than Boussinesq type models. The vvertical structure of the flow is a part of the solution, and becomes more accurate the more layers are included. In SWASH the dispersion characteristics are improved by adding vertical layers rather than increasing the order of derivatives of the dependent variables as in Boussinesq models. The SWASH model contains at most second order spatial derivatives in both time and space, therefore SWASH may run faster than other Boussinesq-type wave models. The SWASH model does not have any numerical filter nor dedicated dissipation mechanism to eliminate short wave instabilities, and lastly the SWASH model does not include other ad-hoc measures to simulate specific processes (like the surface roller model for wave breaking, the slot technique for moving shoreline, the source functions for internal wave generation, or the alteration of the governing equations for modeling wave-current interaction).

WAVE MODELLING IN HARBOUR AREAS

In general waves in harbour areas are determined by the combined effects of wave penetration and locally generated waves. For relatively small harbours the latter effect can usually be neglected, but for large harbour basins and severe wind conditions, local wave growth can contribute significantly or even become dominant over the effect of wave penetration.

Modelling wave penetration in partially sheltered areas is not a straightforward exercise as various processes may affect the choice of the wave model to be used or its settings. An overview of possible relevant processes is given below.

1. The interaction between waves and the entrance channel, where refraction and diffraction effects play a role. Refraction effects may cause focussing of wave energy on the harbour entrance or on particular section of the breakwater. Diffraction effects may alleviate or counteract this focussing Magne et al. (2007), Dusseljee et al. (2014), especially in area with steep slopes.
2. In the harbour basin refraction effects cause a turning of wave energy towards the sides of the dredged shipping lane. These effects are most strongly for the longer wave components and cause a gradual decrease of longer wave energy with increasing distance from the harbour entrance.
3. Diffraction effects around breakwaters and headlands in the harbour cause an increase of wave energy in sheltered areas. As shown by Goda et al. (1978) the effects of diffraction is strongly depended on the amount of directional spreading in the incident wave field, whereas frequency spreading is less important.
4. Wave reflection occurs against the breakwater, revetments, slopes and quay walls in the harbour basin. The effect of wave reflection is to keep part of the wave energy inside the harbour basin. The

amount of wave reflection depends on the type of the coastal revetments, beaches have a low reflection coefficient, where vertical sheet piles have reflection coefficients close to 1. In addition, the amount of wave reflection may depend on the angle of incidence and on frequency. The amount of reflection also depends on water level, especially when low lying areas become flooded. In such a case an initially strongly reflecting quay wall may become partially reflecting and partially transmitting with increasing water level.

5. Wave transmission through partially open breakwater or over partially submerged breakwaters and dams, see e.g. Van der Meer et al. (2005). The magnitude of wave transmission depends on the incident wave conditions, but also on the water level.
6. Harbour oscillations, or seiches, are long period waves caused by resonance effect in the harbour basins. Such waves can be dangerous for moored ships as for certain wave periods the ship movements may become large enough to break the mooring lines.

When modelling in a harbour basin, the importance of each of the above listed effects, including the effect of local wave growth, should be determined before choosing a particular model. In situations or locations where diffraction effects are negligible, phase-averaged models, like SWAN, may provide fairly accurate answers. However, in areas where diffraction effects are expected to play a significant role, phase resolving models are recommended and the possible effects of local wave growth should be added as a kind of correction using either phase-averaged model results or by using parametric wave growth formula.

In the present paper the applicability of the SWASH model for determining the wave penetration in harbour basins is addressed. This is done in a stepwise validation in which we first validate the SWASH model for a simple diffraction cases, followed by a discussion of the transmission and reflection through and against a porous breakwater. Finally, the applicability of SWASH model to determine the amount of wave penetration for a real harbour was tested.

DIFFRACTION

The applicability of SWASH to model diffraction is tested by computing the wave penetration against a semi-infinite breakwater for different amounts of directional spreading. Analytical solutions have been provided by Penny and Price (1944) for uni-directional and mono-chromatic waves, whereas Goda et al. (1978) provide examples of frequency and directionally spread incident wave fields. The SWASH model was applied to compute the wave penetration behind a semi-infinite breakwater using uni-directional and directionally spread waves. The wave model settings were as follows: wave period was 8 s, water depth 1000 m, spatial resolution 5 m, equivalent to 25 points per wave length. For the directional spread waves a spreading of 25 degrees was used.

A snapshot of the surface elevation for both cases is shown in Figure 1. To compare the results of the time domain model SWASH with the analytical solutions, the SWASH model was run for 60 minutes to have a reliable estimate of the diffraction coefficient. This coefficient is obtained by determining the mean wave height for each grid point, followed by dividing through the incident wave height. For the frequency and directionally spread waves this procedure was applied in terms of the significant wave height. For the comparison with the analytical solutions provided by Goda et al. (1978) time averaged output along the lines $y = 2L$ and $y = 4L$, with L the wave length, is shown in Figure 2. It is noted that Goda et al. (1978) derived their diffraction diagrams for a frequency- and directionally wave spectrum and they obtained the solution for a wave spectrum by linear super-position of Sommerfeld solution for individual wave components.

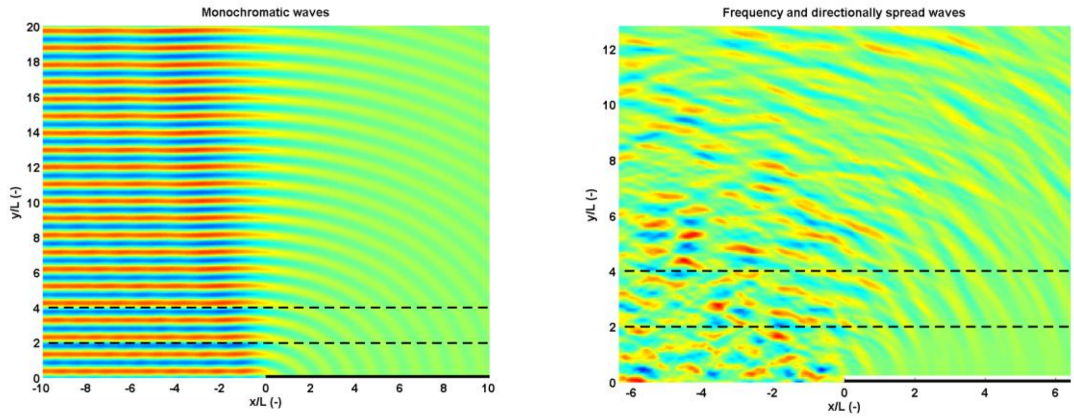

Figure 1. Wave penetration behind a semi-infinite breakwater computed with the SWASH model. Wave period is 8 s. Left panel shows uni-directional waves and right panel shows directionally spread waves. The breakwater is indicated with a black line.

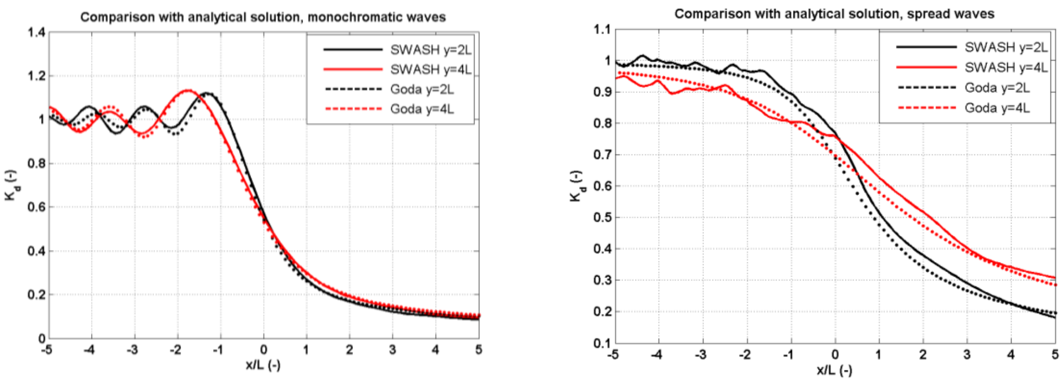

Figure 2. Comparison of the diffraction coefficient for wave height as computed by SWASH (solid lines) and as based on the analytical solutions (dashed lines) of Goda et al. (1978).

The results shown in the Figures 1 and 2 indicate that SWASH is able to reproduce the basic features of wave penetration into a sheltered area. Small differences in results are probably due to the limited time of the simulation. For the directionally spread incident wave conditions it can be seen that the amount of directional spreading diminishes in the shadow zone and is nearly equal to the angle of a line from a point in this area towards the tip of the breakwater.

PARTIAL REFLECTION AND TRANSMISSION

Fixed structures in harbour areas like breakwaters, quay walls and revetments are characterized by a certain reflection coefficient *R* and transmission coefficient *T*. These coefficients are usually determined on the basis of results of physical model experiments (Goda et al., 1967, d'Angremond et al., 1996, Van der Meer et al., 2005). The reflection and transmission coefficients are then determined from an interpretation of the bulk statistics. These coefficients are easy to implement in phase-averaged models like SWAN and the required reflection and transmission is exactly evaluated. For phase-resolving models like SWASH or IH2VOF (Lara, 2005) reflection and transmission cannot be handled in the same way as for phase-averaged models due to conceptual differences; as no average like a significant wave height exist on this scale. Instead, partial reflection and transmission are simulated by mimicking the hydrodynamic characteristics via porous layers. The SWASH model has the option to include porous layers in the schematisation. The user then has to specify the porosity (a value between 0 and 1), the grain size of the dissipating elements in the porous layer and the height of the porous structure. Additionally, coefficients can be specified to scale the loss of energy due to laminar of turbulent friction using the well-known Darcy-Forchheimer relations. The use of porous layers has the potential advantage that directional and frequency dependence of wave reflection is automatically accounted for.

In practise, it is still difficult to determine the relationship between the characteristics of porous layers and the resulting reflection and transmission coefficients. Madsen (1983) investigated wave reflection from a vertical permeable wave absorber and he proposed some relationships. Mellink (2012) performed physical model experiments to measure the transmission and reflection coefficients for permeable breakwaters. Van den Bos et al. (2014) extended the work of Mellink to investigate the ability of various wave models to reproduce wave reflection and transmission through porous breakwater. The results of Van den Bos et al. (2014) indicate that SWASH is able to reproduce the reflection and transmission coefficient of a porous breakwater.

LIMASSOL HARBOUR

The city of Limassol is located along the south coast of the Mediterranean island of Cyprus, see Figure 3 for a situation sketch. In 1990's Delft Hydraulics (Dekker, 1991) carried out physical model experiments to assess the consequences of a port extension. Physical model experiments were carried out on a scale of 1:100 for three main directions of wave incidence, i.e. 80°N, 100° and 130° (Reijmerink, 2012). From a total of 46 scenarios, the one most resembling the present situation was selected for validating the SWASH model. This condition has an incident wave direction of 80°N and a corresponding the 1-year extreme condition is represented with a JONSWAP spectrum with a peak period of T_p = 7 s, a peak enhancement factor of γ = 3.3, a significant wave height of H_s = 2.5 m and a directional spreading of σ = 31.5°. It is noted that this condition was also used by Reijmerink (2012) using the phase-averaged SWAN model and the mild-slope model PHAROS and by Adytia (2014) using a variational Boussinesq-type wave model.

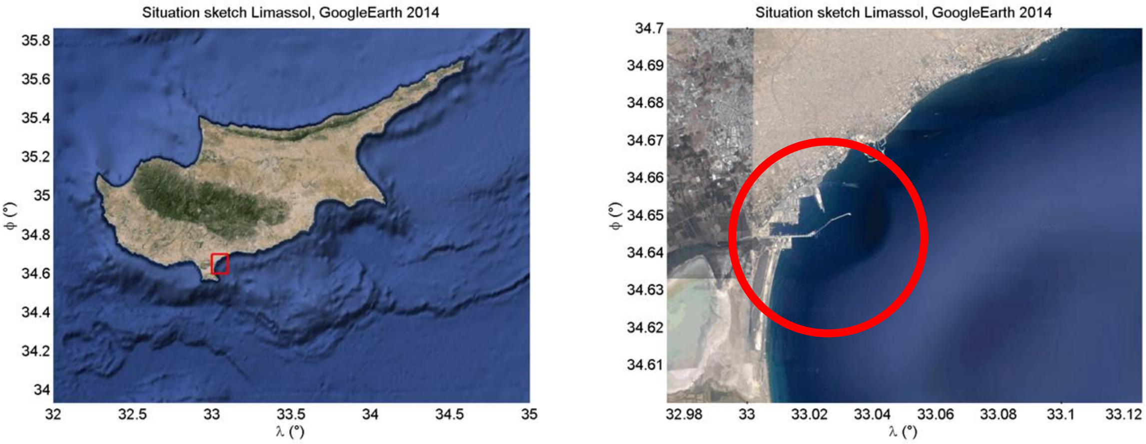

Figure 3. Location Limassol harbour on the Mediterranean island of Cyprus.

The physical model setup is shown in left panel of Figure 4 and the numerical model setup is shown in the right panel of Figure 4. The 28 output locations are indicated with circles labels. At each location time series of surface elevation were measured from which the significant wave height H_{m0} and peak period T_p were determined. Unfortunately, the original time series or processed wave spectra were not saved due storage limitations.

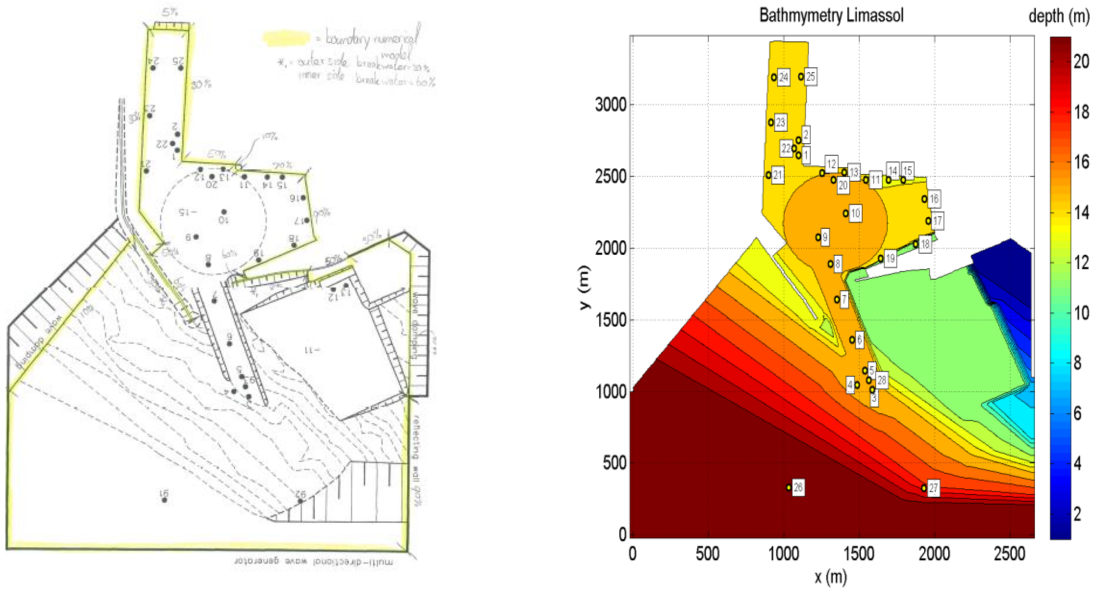

Figure 4. Model setup of physical model experiment for Limassol harbour (Dekker,1991) (left panel) and schematisation in SWASH (right panel).

NUMERICAL SET-UP

In the SWASH model setup, the bathymetry was given at a resolution of 5 m by 5 m. Along the left breakwater the bathymetry was smoothed to avoid steep slopes that may cause unwanted instabilities. The computational resolution was 5 m in *x*-direction and 2 m in *y*-direction. The breakwater and quay walls in the harbour area were lined with a porous strip with a width of 5 m with a grain size of 0.1 m to mimic their partial reflection characteristics. In contrast to Adytia (2014) no spatial variation of reflection characteristics were specified. At the upper end of the harbour a sponge layer with a width of 150 m was specified to absorb outgoing waves. The computation was carried out in the non-hydrostatic mode with 2 layers in the vertical for proper dispersion characteristics. Bottom friction was included which is based on the Manning formula with a Manning coefficient of 0.019 $sm^{-1/3}$. Wave breaking criterion was employed to prevent underestimation of the amplitude dispersion while using a relatively coarse resolution in the vertical (Smit et al., 2013). A background viscosity of $\nu = 10^{-5}$ m^2/s was applied to couple the vertical layers.

The incident wave condition was specified as a JONSWAP spectrum with a peak enhancement factor of $\gamma = 3.3$ and a $\cos^2(\theta)$ directional spreading. Some tuning was needed to properly reproduce the wave height at the first 2 output locations 26 and 27 (see Fig. 4). The resulting boundary conditions were a significant wave height of $H_s = 2.91$ m and a peak period of $T_p = 7.06$ s and an incident wave direction of 110° (Cartesian convention). A similar tuning of the wave boundary conditions can be observed in the results of Adytia (2014).

The simulations were carried out with an initial time step of 0.05 s for a duration of 25 minutes. This was sufficiently long to achieve a stationary solution. The Courant number for stability was set to 0.5. Times series of surface elevation were collected at all 28 output locations and processed to compute the frequency spectrum and the related significant wave height H_{m0} and peak period T_p. For the last 10 minutes the instantaneous square of the surface elevation was summed to estimate the wave variance at each location of the computational grid. Based on this variance the spatial variation of the significant wave height was estimated.

RESULTS

We performed two simulations to estimate the effect of directional spreading on the amount of wave penetration in the sheltered area. In the first computation we imposed the above specified wave height, period and direction conditions, but with uni-directional waves. In the second computation we added the desired amount of directional spreading to the wave boundary condition. Figure 5 shows a snapshot of the surface elevation. The effect of reflection, diffraction and refraction are visible in the results. The amount of wave penetration in terms of the significant wave height H_{m0} is shown in Figure 6. The most noticeable feature is the pronounced tongue of wave energy entering the harbour basin.

Figure 7 shows a snapshot of the surface elevation for the conditions including directional spreading in the boundary condition. Also for this situation the effects of reflection and diffraction in the harbour basin can clearly be seen. The spatial variation of the significant wave height H_{m0} is depicted in Figure 8. The effect of refraction along the channel edges and diffraction in the sheltered area are clearly visible. These results compare rather well with similar results of Reijmerink (2012) and Adytia (2014). Lastly, Figure 9 shows the comparison between observed and simulated significant wave height H_{m0} in all 28 locations. (The variation of the peak period was insignificant.) In general the agreement between SWASH and the observed values is rather good, although at some locations the differences are still relatively large.

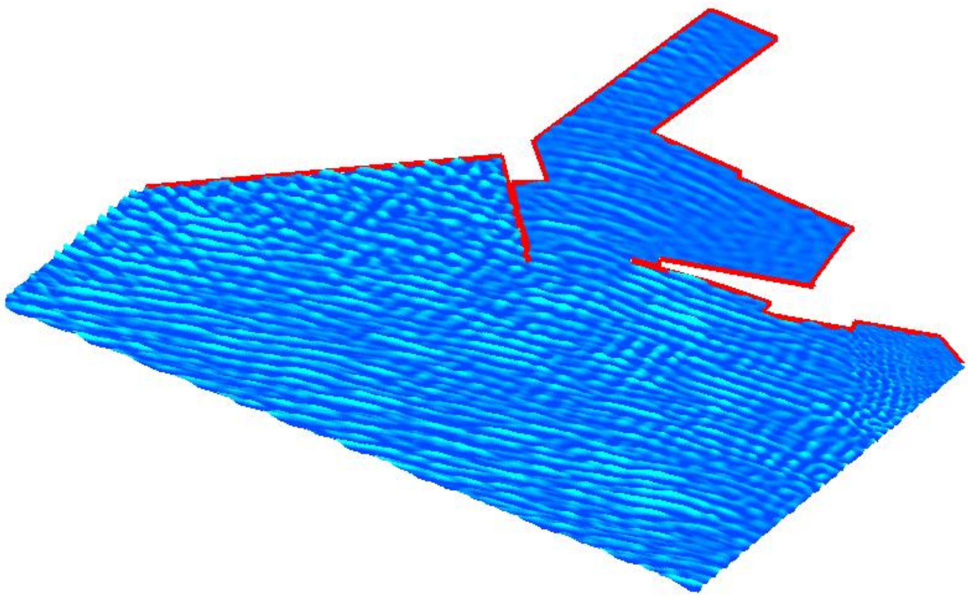

Figure 5. Snapshot of surface elevation after 25 minutes for monochromatic wave incidence.

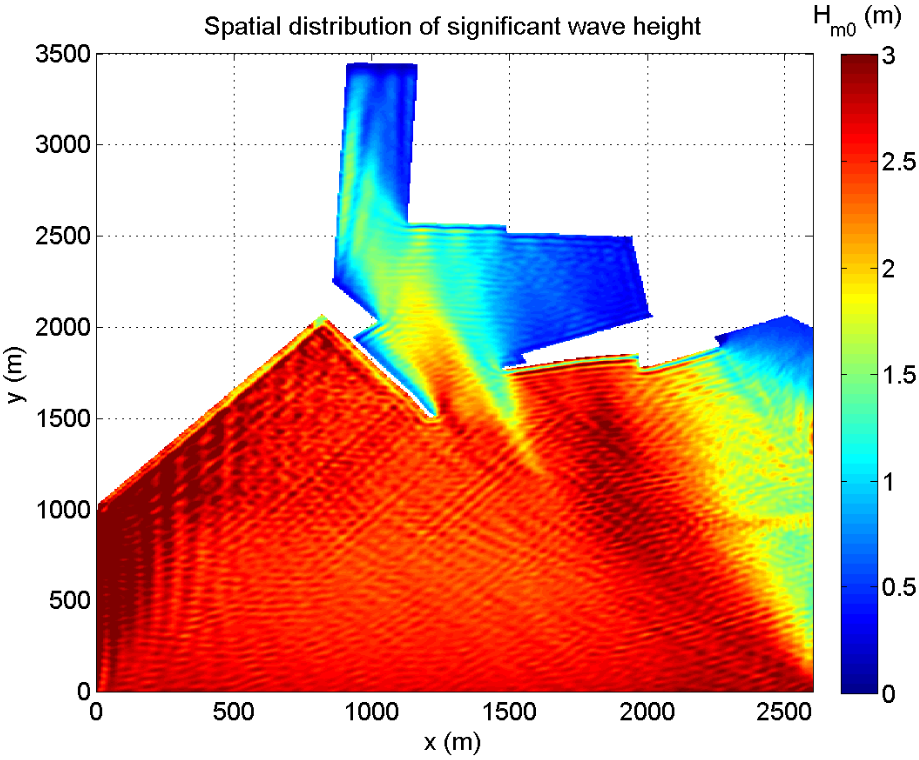

Figure 6. Spatial variation of significant wave height H_{m0} for monochromatic wave incidence.

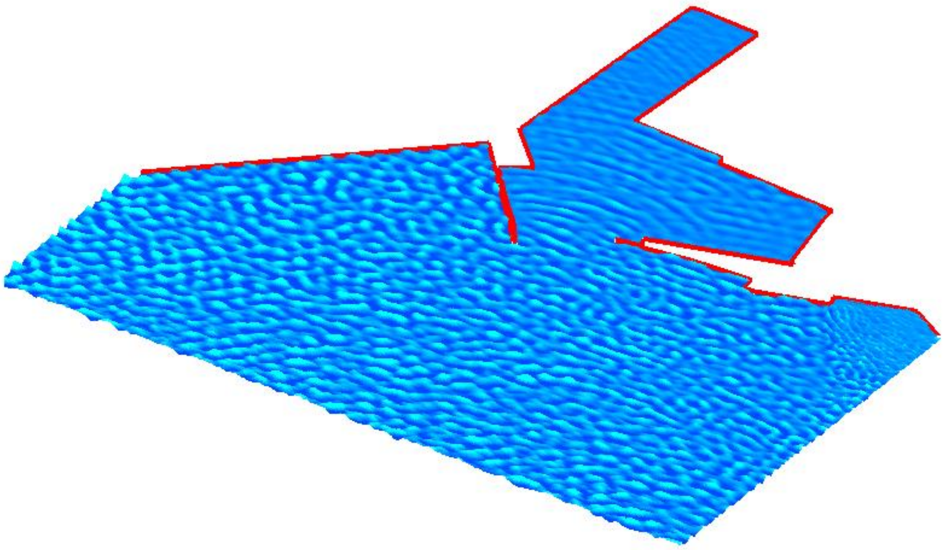

Figure 7. Snapshot of surface elevation after 25 minutes for the Limassol test condition with directionally spread waves at the boundary.

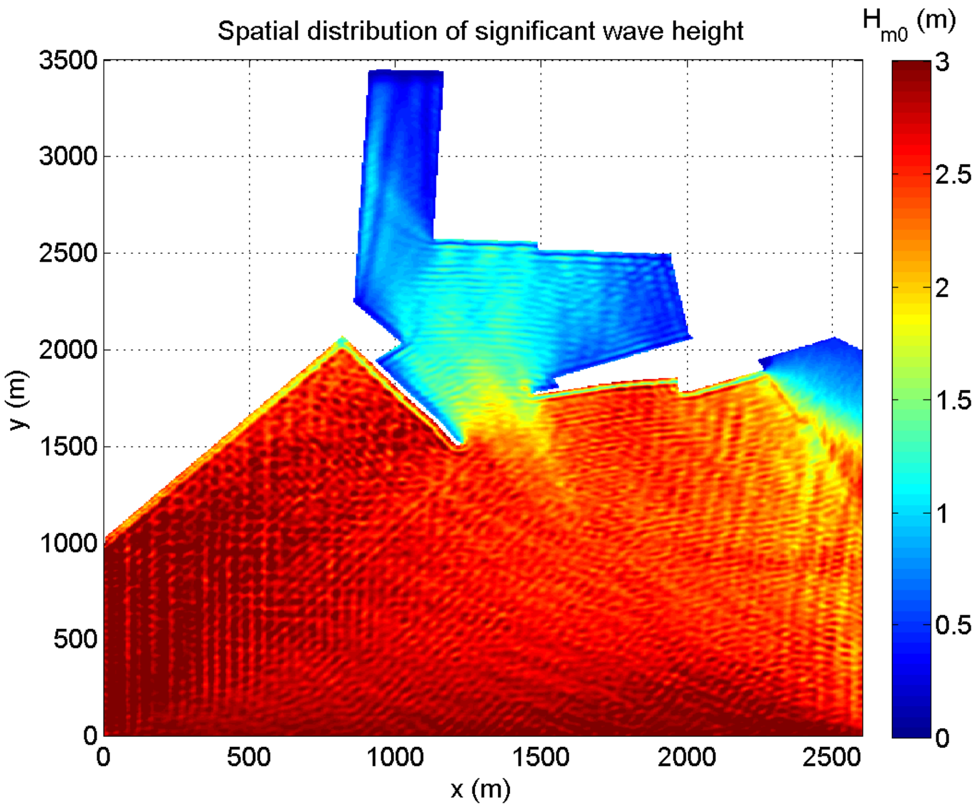

Figure 8. Spatial variation of significant wave height H_{m0} for directionally spread wave incidence.

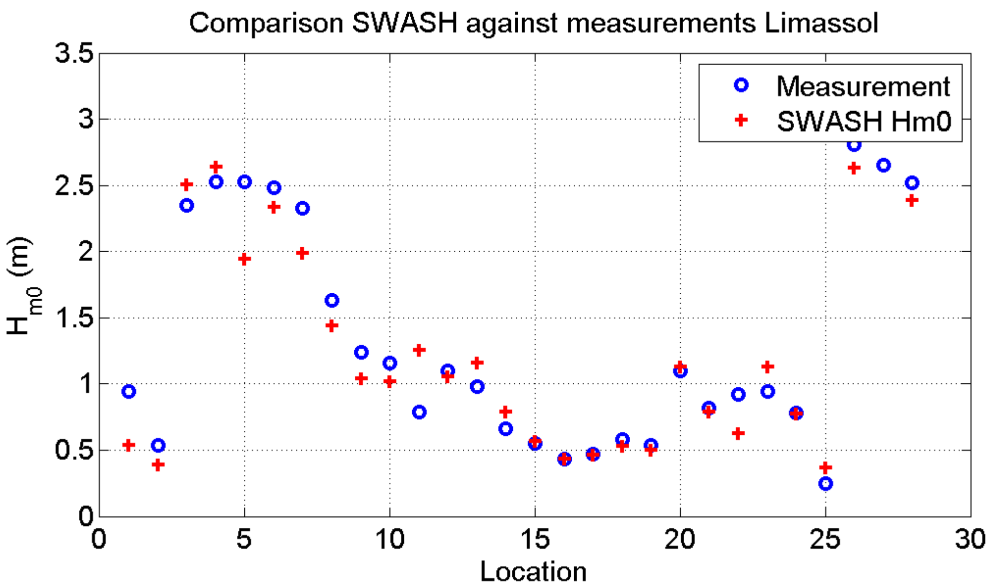

Figure 7: Comparison of computed and observed significant wave height H_{m0}.

CONCLUSIONS

The results presented in this paper show that the non-hydrostatic SWASH model is able to accurately reproduce the effects of diffraction behind a semi-infinite breakwater for both uni-directional and directionally spread waves, and the partial reflection and transmission through a porous breakwater. For the Limassol harbour case, the computed spatial variation of significant wave height H_{m0} and peak period T_p compare well with the measurements. Based on these results we conclude that SWASH can be used for wave penetration studies in harbours and partly sheltered area.

Despite these promising results, further work is needed to better schematize the partial reflection of vertical quay walls using porous strips. A systematic analysis is recommended to infer the relationship between characteristics of porous layers and the resulting reflection coefficient as a function of wave period and angle of incidence.

The Limassol data set has proven to be a useful one for a first validation of the SWASH model to compute the wave penetration in partly sheltered areas. Still, this test case has limited applicability as no time series of wave spectra were stored. Also, some uncertainties still exist regarding the reflection characteristics of the slopes and revetments. Therefore, additional well documented test cases are needed to validate wave propagation model with respect to the wave penetration in partly sheltered areas.

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