WAVE TRANSFORMATION ON CORAL REEFS: COMPARISON OF A CFD MODEL AND PHYSICAL MODEL TESTS OF A MALDIVIAN REVETMENT.

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INTRODUCTION

Coral atolls and islands are threatened by flooding and coastal erosion from rising sea levels due to climate change. Structures like revetments, breakwaters, and other coastal protection schemes can be implemented to mitigate these problems. However, designing optimized coastal structures on islands bordered by coral reefs has proven to be a challenging task due to the complex reef and wave interaction (Jensen, 1991; Jensen, Sloth and Jacobsen, 1998). Often the reefs in these tropical regions have a steep seaward profile until a certain depth, whereafter the reef suddenly becomes flat with a mild slope. When offshore waves reach the reef, it can result in plunging wave breaking, a wave set-up, and energy transfer from the peak frequency to lower frequencies resulting in long period wave motions.
Under these conditions, it is difficult to predict the rate of overtopping as the complex hydrodynamics are not covered in standard overtopping formulas. Furthermore, the standard spectral wave models, on which the overtopping formulas often are based, cannot describe the transformation of offshore waves over the reef as the models are not able to resolve the physics of this violent water motion.

Recently, Liu et al. (2021) and Love et al. (2022) have proven that the wave transformation over reefs and overtopping rates can be calculated by the open-source phase-resolving SWASH-model. In the present paper, the wave transformation over the reef of an irregular wave train is solved with a CFD model based on the open-source library Open Field Operation And Modification (OpenFOAM (n.d.)).

In connection with the hydraulic study for a detailed design of a revetment on Fuvahmulah in the Maldives, the OpenFOAM CFD model is applied to obtain the hydrodynamic design parameters. The wave dynamics on the reef, the revetment overtopping rates, and hydrodynamic forces derived from the numerical model are compared with results from a physical model conducted by the Danish Hydraulic Institute (DHI). A similar analysis has been conducted by Yao et al. (2022) who investigated the wave transformation and runup over rough fringing reefs using OpenFOAM. However, Yao et al. (2022) only considered regular waves, while the present study focuses on irregular wave time series.

METHODS

A 360 meters long 2D wave flume with a water depth of 21.43 meters is set up in an OpenFOAM CFD model. On the reef, a revetment with porous armour and filter layers is placed. The waves are generated in a relaxation zone stretching from the offshore boundary and 150 meters landward. The boundary conditions are applied through the Waves2Foam library (Waves2Foam (n.d.)). The seabed and the reef surface are treated as impermeable solid walls with a no-slip condition. A seabed roughness of 5 cm is implemented in the model via a k-omega SST turbulence model. The parameters that are calculated are the velocity in the x and y direction, P, alpha, k, and omega.

The surface elevation in the CFD model is recorded with numerical wave gauges (WG) at alpha=0.5 placed at six distinct locations: One wave gauge offshore to monitor the incoming waves, and five wave gauges with 20 meters distance from the reef edge to the revetment toe to monitor the wave transformation over the reef. A sketch of the numerical wave flume is illustrated in Figure 1.

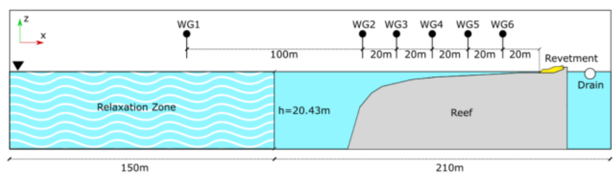

Figure 1: Sketch of numerical wave flume. Note: z axis is out of scale for illustration purposes.

The overtopping rates are extracted from the CFD model by calculating the discharge of water over the revetment. Furthermore, the horizontal force on the rear concrete wall (illustrated in Figure 2) is extracted. A JONSWAP wave spectrum is used to generate the sea state. The model is simulated for 15 minutes.

The mesh consists of squares. In the model domain, several refinement regions are defined, and the mesh resolution is gradually increased in the landward direction. The largest mesh elements have a resolution of 1x1m. The area around the reef has a resolution of 0.5x0.5m, and the area around the concrete wall has a resolution of 0.25x0.25m. The model mesh at the revetment cross-section is illustrated in Figure 2. The figure also show the porous armour and filter layers.

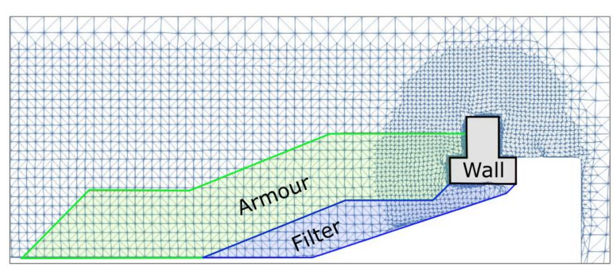

Figure 2: Model mesh and revetment cross-section.

The results of the numerical model are compared with the results from a 1:30 scale physical model conducted by DHI. The physical model has the same reef profile, model setup and revetment cross-section. This makes it possible to directly compare the results from the numerical test against the results from the physical test.

In the physical model, the target significant wave height (H_{m0}) and peak wave period (T_p) was 4.5 meters and 12 seconds respectively. The target conditions in the model were not completely matched at the primary target location, 200 meters from the revetment toe. To match the incoming wave from the physical model in the numerical model, H_{m0} was set to 4.8 meters and T_p was set to 11.7 seconds at the boundary. A total number of 25 frequencies are included in the spectrum of the numerical model.

RESULTS

In agreement with the findings from Jensen, 1991; Jensen, Sloth and Jacobsen, 1998, the CFD model shows a significant rise in the mean water level on the reef. The increase in the water level on the reef can be interpreted as a static water level setup, caused by violent wave breaking on the edge of the reef. At WG6 (20 meters from the revetment toe) the static water level setup is 0.56 meters. The static water level setup becomes smaller once we move further offshore. At WG5 (40 meters from the revetment toe) the static water level setup is 0.26 meters, and at WG4 (60 meters from the revetment toe) the water level setup is 0 meters. The waves push a water body onto the reef plateau, where it is trapped by the energy of the incoming waves.

In addition to the static water level setup, a long-period surf beat is present on the reef. The surf beat is a result of the bound long-period wave connected to the wave groups being released on the reef when the individual waves in the wave group break. The raw surface elevation along with the surf beat component of the surface elevation is illustrated in Figure 3. From the figure, it is seen, that the long periodic surf beat has a wave height of around 0.9 meters. From a design point of view, the surf beat only has a small impact on the rock stability in the armour layer, however, it has a big impact on the overtopping rates.

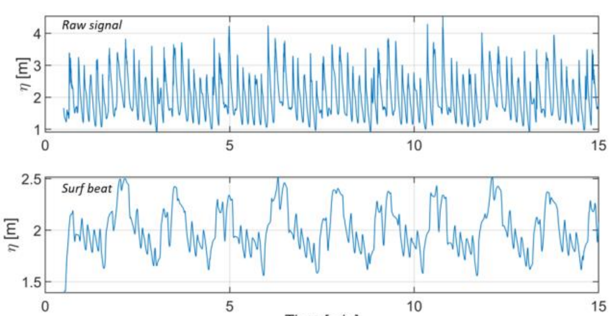

Figure 3: Raw surface elevation (top) and long-periodic surf beat at WG6.

An example of the wave breaking on the reef along with an overtopping event from the numerical model is illustrated in Figure 4. The larger waves in the wave train are breaking in the area around WG3 (80 meters from the revetment toe). The figure clearly shows how the wave is plunging on the reef edge, and how a mixture of air and water is present in the porous armour layer as a result of the turbulent mixing of air and water.

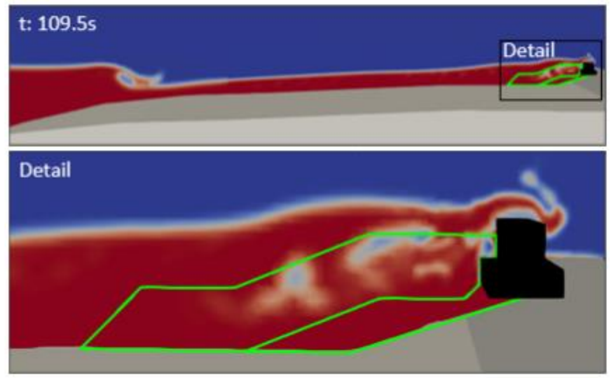

Figure 4: Top: Wave breaking on the reef. Bottom: Example of overtopping.

The significant wave height at the 6 different wave gauges from the CFD model and the physical model can be seen in Table 1. The table shows that the incoming significant wave is close to identical in the two models. WG3 is located on the edge of the reef, where the largest waves are breaking. The difficulty of measuring the surface elevation at the breaking point for a plunging wave can be one of the explanations for the relatively large difference in significant wave heights between the two models at WG3. However, by looking a WG4, WG5 and WG6, the CFD model seems to do a fairly good transforming the wave over the reef. The differences between the two models might also be found in the differences in simulation time: The physical model was simulated for 6 hours (in real scale) whereas the numerical model is simulated for 15 minutes.

Table 1: Difference in significant wave height (H_{m0}) between CFD and physical model

Wave gauge	WG1	WG2	WG3	WG4	WG5	WG6
Distance from toe [m]	200	100	80	60	40	20
H_{m0} CFD model [m]	4.65	4.94	5.11	4.92	3.38	2.75
H_{m0} physical model [m]	4.64	5.05	5.72	4.64	3.12	2.81
Difference [%]	0.22	-2.18	-10.66	6.03	8.33	-2.14

The exceedance probability of the wave heights at WG2 to WG6 is illustrated in Figure 5. The figure in general shows a good agreement between the physical and numerical model results. The curves are almost perfectly aligned for the smaller wave heights with high exceedance probability. For the larger waves, the curves start to deviate at some of the offshore wave gauges. Once again, the differences between the two curves might be explained by the differences in simulation time: When increasing the simulation time, the possibility of observing a large wave increases. It is therefore expected to have larger waves in the 6 hour long physical test compared to the 15 minutes long numerical simulation.

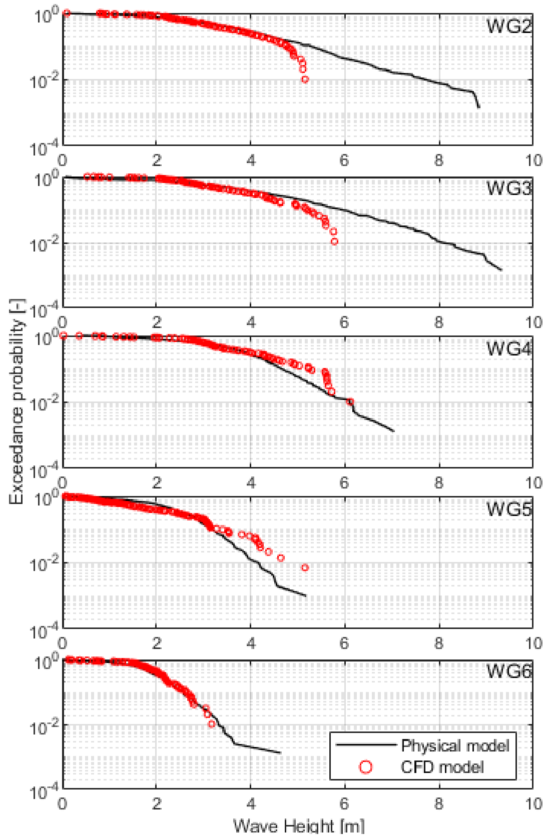

Figure 5: Exceedance probability of wave heights at WG2, WG3 and WG5. The legend applies to all figures. Note: Data from the numerical model are not exact but extracted from a figure.

The overtopping rates in the CFD and physical model can be seen in Table 2. With a difference between the two models of 26.9 %, the CFD model has a higher overtopping rate. It is worth mentioning, that the overtopping rate is determined by relatively few overtopping events in the numerical model. The comparison is therefore resting on a relatively small dataset.

Table 2: Difference in overtopping rates between the CFD and physical model.

Overtopping CFD model	41.3	l/s/m
Overtopping physical model	32.6	l/s/m
Difference	26.9	%

Figure 6 illustrates the exceedance probability in the horizontal force on the rear concrete wall in the two models. In general, the forces in the two models are in the same order of magnitude, with a tendency towards slightly higher fluctuations in the physical model. The 1% highest force in the CFD and physical model is 40 and 46 kN/m respectively, resulting in a difference of 13 %.

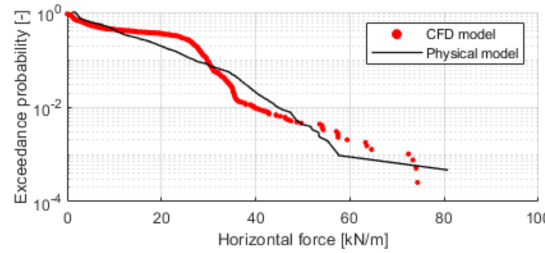

Figure 6: Exceedance probability of horizontal force on the concrete wall. Note: Data from the numerical model are not exact but extracted from a figure.

CONCLUSION

In general, we find a fairly good agreement between the numerical and physical model when it comes to wave transformation over the reef, overtopping rates and horizontal force calculations. The numerical model especially gives a good description of the horizontal force on the T-shaped concrete wall. The numerical model showed a static water level setup on the reef and a dynamic water level setup from the surf beat, which have a large impact on the overtopping rates. Both the results from the numerical and physical models have some degree of uncertainty. The physical model can have scale effects and possible measurement errors, and the numerical model can have uncertainties like discretisation errors and other modelling-related errors. Since the CFD model often will be faster to set up and run compared to conventional physical tests, it has some clear advantages from a design perspective. In the CFD model it is furthermore possible to make changes in the model setup after running some tests, which can be a costly affair when conducting physical tests. The CFD model should, however, be used with care, since the results can be highly sensitive to model parameters like roughness, turbulence formulations and mesh dimensions.

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