A VALIDATION OF WAVE LOADS ON CREST WALLS ON TOP OF COMPOSITE BREAKWATERS USING OPENFOAM

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The design of crest walls is often based on empirical formulations, physical model tests, numerical models and a fair amount of expert judgement. The present work validates the prediction of wave induced forces on the front face of crest walls on top of composite breakwaters in the numerical model OpenFOAM. The results show that OpenFOAM is able to capture the shape and order of magnitude of the force events caused by non-breaking and heavily breaking waves. In addition, a calibrated model predicts the highest wave induces forces caused by breaking waves with errors lower than 20%.

Keywords: wave loads; OpenFOAM; composite breakwater; crest wall; numerical model

INTRODUCTION

Breakwaters are structures designed to protect ports and shores against the incoming wave attack. Often, to reduce the overtopping volumes without increasing the height and amount of material of the breakwater, a crest wall or crown wall on top of the breakwater is placed. These L-shaped concrete elements besides improving the overtopping performance of the breakwater, also provide access, a working platform and can be used to carry pipelines or conveyors.

Crest walls on top of breakwaters are subjected to severe wave attack. When the wave loads exerted on the crest wall surpass a certain threshold, they can lead to one of the crest wall failure mechanisms: cracking, sliding, overturning or geotechnical failure. This can be critical for the coastal protection since a failure of the crown wall can lead to a failure of the entire breakwater (Pedersen, 1996). To obtain a safe and optimal design, an accurate estimation of the wave loads on the crest wall is required.

The design of crest walls on top of breakwaters is often based on empirical formulations, physical model tests, numerical model simulations, and a fair amount of expert judgement. Each technique has its own pros and cons. The empirical formulas must often be applied outside their range of validity, where they fail to predict accurately the wave induced forces (Nørgaard et al, 2013 and Jacobsen et al., 2018). Physical modelling also has its own shortcomings. When breaking waves hit the structure, the location of the maximum pressures at the crest wall is still not well known due to the high spatial variability. By using a coarse array of pressure sensors, the forces estimated in the physical flume can underestimate the actual forces experienced by the wall (Ramachandran et al, 2013).

In the last decades, due to the increase capabilities of the computers, numerical modelling has become an attractive alternative in simulating wave-structure interactions. One of the widely used numerical models is OpenFOAM, which solves The Reynolds Averaged Navier-Stokes equations (RANS) using as surface tracking technique the Volume of Fluid (VOF) method (RANS-VOF model). Although many wave processes have been simulated and validated in OpenFOAM, including wave overtopping for impermeable structures, porous breakwaters and crest walls on top of rubble mound breakwaters (Jensen et al, 2014, Karagiannis et al, 2015, Patil, 2019, Boersen et al, 2019, Chen et al 2021, Irías Mata and Van Gent, 2023); wave interaction with porous structures and open filters (Jensen et al 2014, Jacobsen et al, 2015, Jacobsen et al, 2017 and Van Gent et al, 2018), wave interaction with Tetrapods (Lee et al, 2019), wave breaking (Brown et al, 2016, Devolder, 2018 and Larsen and Furhman, 2018) and wave induced forces (Jacobsen et al, 2018 and Castellino et al, 2021); estimating loads on crest walls in a numerical wave flume is still at its early stages. On that account, the present work validates the prediction of wave induced forces on the front face of crest walls on top of a breakwater. A scale model, performed by DHI, of the Holyhead breakwater (see Fig. 1), located in Wales, is used for validation of the numerical model developed in OpenFOAM.

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Figure 1. Picture of modelled breakwater: Holyhead breakwater.

MATHEMATICAL MODEL

The numerical flume consists of the coupling of the CFD model named OpenFOAM (Weller et al., 1998) and the fully nonlinear potential flow solver OceanWave3D (Engsig-Karup et al., 2009) implemented by Paulsen et al. (2013). The offshore wave conditions until the vicinities of the breakwater, before the point of wave breaking are simulated in OceanWave3D. The wave breaking and the wave-structure interaction is computed by OpenFOAM. The capabilities of modelling wave-structure interaction in OpenFOAM were added by means of the waves2Foam library where a module for wave generation (Jacobsen et al., 2012), wave interaction with porous media (Jensen et al., 2014) and the porous boundary conditions (Jacobsen et al., 2018) are included.

HYDRODYNAMIC MODEL

The hydrodynamic model is based on the volume averaged two-phase version of the Navier-Stokes equations to account for permeable structures (Van Gent, 1994 and Van Gent, 1995a,b). They defined the velocity as the filter velocity, which is the spatial averaged velocity over a certain area including the area occupied by the stones. The momentum and continuity equation are written as:

$$(1 + C_m)\frac{\partial}{\partial t}\frac{\rho \boldsymbol{u}_f}{n_p} + \frac{1}{n_p}\nabla\frac{\rho}{n_p}\boldsymbol{u}_f\boldsymbol{u}_f^T = -\nabla p^* + gx\nabla\rho + \frac{1}{n_p}\nabla\mu\nabla\boldsymbol{u}_f - F_p \quad (1a)$$

$$\nabla u = 0 \quad (1b)$$

Here, C_m is the added mass coefficient that accounts for the transient interaction between grains and water, $\boldsymbol{u}_f$ is the filter velocity vector in Cartesian coordinates, n_p is the porosity of the permeable structure, $\nabla=\partial/\partial x+\partial/\partial u+\partial/\partial z$, p^* is an excess pressure, g is the gravity acceleration, x=[x,y,z] is the Cartesian coordinate vector, μ is the dynamic molecular viscosity and F_p is the resistance force due to the presence of the porous media. This implementation uses a version of the Navier-Stokes equations which does not account for the eddy viscosity; thus, a turbulence closure model is not necessary. This assumption was validated by Jensen et al. (2014) and Jacobsen et al. (2015), when there is little energy dissipation caused by wave breaking and large energy dissipation caused by the structure.

The VOF method is used to track the free surface between the air and water interface by adding an advection equation:

$$\frac{\partial\gamma}{\partial x} + \frac{1}{n_p}\left[\nabla\boldsymbol{u}_f\gamma + \nabla\boldsymbol{u}_r(1-\gamma)\gamma\right] = 0 \quad (2)$$

where γ is the indicator function of the VOF field and $\boldsymbol{u}_r$ is a relative velocity introduced by to sharpen the interface resolution (Berberović et al., 2009). The indicator function takes values between 0 and 1, with values of zero when the cell is filled with air, values of 1 when is filled with water and intermediate values when the two phases are present inside the cell. The factor $1/n_p$ was introduced in Eq. (2) by Jensen et al (2014) to ensure the mass conservation when the fluid passes through porous media. This factor accounts for the fact that a given volume is emptied or filled faster when sediment grains are also included inside that volume. The indicator function is then used to estimate the fluids densities (ρ) and viscosities (μ):

$$\rho = \gamma\rho_w + \rho_a(1-\gamma) \; and \; \mu = \gamma\mu_w + \mu_a(1-\gamma) \tag{3}$$

The subscripts *a* and *w* represent air and water, respectively. The fluids densities and viscosities are weighted average based on the distribution of water and air in each control volume, i.e. in each cell. After computation, the fluid properties at each grid cell are used in the momentum equations.

Porous media resistance forces

The presence of the porous media is included in the hydrodynamic model by means of the added mass coefficient (C_m) and the resistance term (F_p). To resolve these terms, the extended Darcy-Forchheimer equation is applied as a closure model:

$$F_p = a\rho\boldsymbol{u}_f + b\rho\left\|\boldsymbol{u}_f\right\|_2\boldsymbol{u}_f \tag{4}$$

When the first term dominates, the flow behaves as laminar while if the second term dominates, the flow is turbulent. The parameters *a* and *b* are resistance coefficients that are evaluated following the parametrisation derived by Van Gent (1995a,b), where the effect of the oscillatory porous flow was included by means of the KC number (Keulegan-Carpenter number):

$$a = \alpha\frac{(a-n_p)^2}{n_p^3}\frac{\nu}{\rho n_{n50}^2} \; and \; b = \beta\left(1+\frac{7.5}{KC}\right)\frac{1-n_p}{n_p^3}\frac{1}{d_{n50}} \tag{5}$$

α and β are calibration coefficients depending on grading and shape of the grains, υ is the kinematic molecular viscosity and d_{n50} is the median grain diameter of the porous structure. The inertia term in the extended Forchheimer-Darcy equation was already included in the momentum equation by means of C_m.

Ventilated boundary condition

Jacobsen et al. (2018) propose a technique to solve the spurious entrapment of air between water surface and structural elements. The phenomena where the waves in air-filled cavities exert large forces on structures was seen experimentally and numerically, resulting in inaccurate predictions of wave loads on crest walls. At the moment of their research, the existing techniques involve introducing small tubes through a structure to allow air ventilation. However, this led to highly time-consuming numerical simulations because all the volume of air was transported through the thin tube causing high air velocities, thus, limiting the time-step of the numerical model. The proposed solution by Jacobsen et al. (2018) is the use of a permeable boundary condition at the structure that allows for air ventilation without restricting the time-step. This technique is also known as the ventilated boundary condition:

$$p_b^* = p_{ref}^* + \frac{\rho}{2}\frac{\xi_f}{e_p^2}|u^\perp|u^\perp \tag{6}$$

Where $u^\perp$ is the filter velocity normal to the structural element, e_p is the degree of openness of the element and ξ_f is the loss coefficient based on $u^\perp$. Jacobsen et al (2018) found that a 3% degree of openness and a loss coefficient of 1.5 provided good results for the prediction of forces on crest walls.

PHYSICAL MODEL TESTS

The dataset used as validation material was obtained from the first physical modelling campaign for a cross-section of the Holyhead breakwater. For all tests, a standard JONSWAP wave spectrum with a peak enhancement factor of 3.3 was applied. The wave generating system has a wave reflection compensation module able to absorb the reflected waves, reducing the undesired re-reflection at the wavemaker (DHI, 2019).

Four physical tests were selected to validate the performance of OpenFOAM in predicting the wave induced forces on the front face of crest walls. Non-breaking and breaking waves (operational and extreme wave conditions) were tested along with two different breakwater geometries; one with an impermeable foreshore and one adding a Tetrapods layer of 30 m wide and 5.2 m thick in front of the crest wall, named hereafter Baseline layout and Tetrapods layout respectively (see summary in Table 1 and cross sections in Figure 2).

Table 1. Boundary conditions for the numerical and physical flume. H_{m0} is the significant wave height, T_p is the peak period and h is the water depth.

Case	Layout	Hydraulic conditions	h [m]	H_{m0} [m]	T_p [s]
1	Baseline	Operational	0.513	0.044	1.025
2	Baseline	Extreme	0.513	0.103	1.468
3	Tetrapods	Operational	0.513	0.044	1.025
4	Tetrapods	Extreme	0.513	0.103	1.468

Source: DHI, 2019

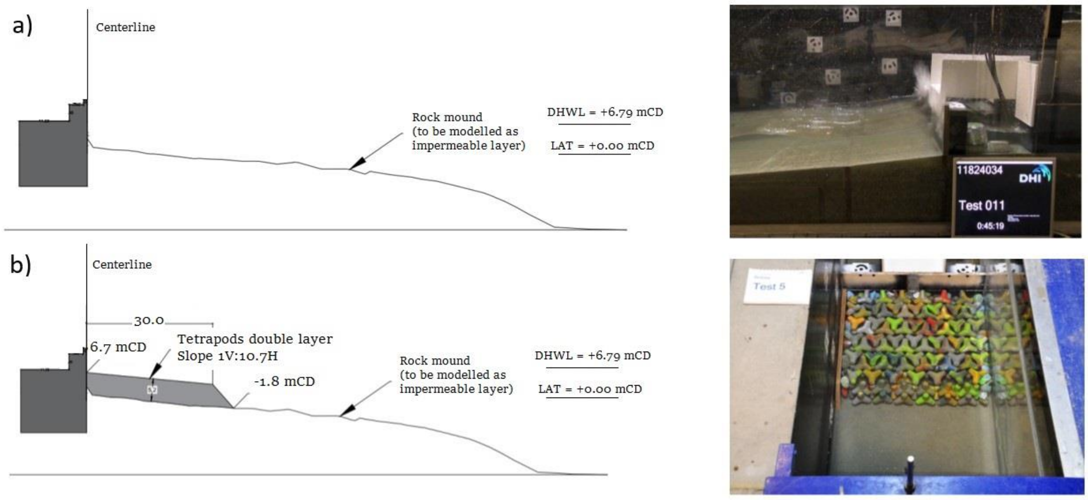

Figure 2. Model cross-sections in the wave flume. a) Baseline layout. b) Tetrapods layout. Left panel: profile and measurements in prototype scale. Right panel: model set up in the laboratory. Adapted from DHI, 2019

During the tests, the surface elevation was recorded by 11 wave gauges – 5 located offshore (6 m, 6.4 m, 6.75 m, 7 m and 7.1 m from the wave paddle), 5 located just before the rubble mound (16.5 m, 16.9 m, 17.25 m, 17.5 m and 17.6 m from the wave paddle) and 1 placed before the toe of the new armour layers (18.5 m from the wave paddle). The wave loads on the wall were measured by pressure transducers located in the centre of the front side of the wall at 5 different heights (10 mm, 46.5 mm, 83 mm, 119.5 mm and 156 mm measured from the model bathymetry to the centre of the sensors).

NUMERICAL MODEL TESTS

The 2DV numerical flume consists of an OpenFOAM model coupled with an OCW3D model. The numerical flume illustrated in Figure 3 was defined with a total length of 26.4 m and a height of 0.8 m, to mimic the physical flume. Eleven wave gauges were positioned along the numerical flume at the same locations as in the physical flume to capture the water surface elevation. The breakwater and the crown wall were located 15.5 m and 20 m from the inlet boundary. This is the same distance between the wave maker and the structures as in the physical model. To reproduce the same wave climate as in the physical flume, the laboratory wave paddle displacement time series is used in the numerical flume to generate the offshore waves. To be used as sound input data, the wave paddle signal was interpolated to a smaller Δt by using FFT (Fast Fourier Transform) signal reconstruction. This step was necessary due to the fact that the paddle data was too coarse (recorded every 0.2 s), leading to large underestimations of the incoming wave conditions. The interpolation procedure consisted in applying the FFT to the paddle position time series to obtain the phases and frequencies and then applying the IFFT (Inverse Fast Fourier Transform) to reconstruct the time signal with a smaller Δt by using the already estimated phases and frequencies. In this case, FFT signal reconstruction of the wave paddle data was used rather than linear interpolation of this data because the later method was not sufficient. Applying linear interpolation led to inaccurate results associated with large underestimations of the incoming wave conditions (exemplified in Figure 4).

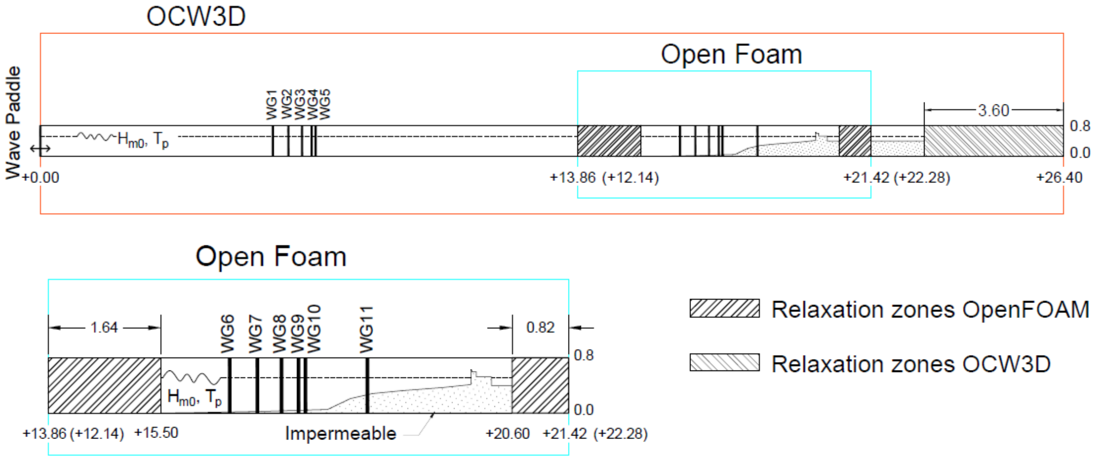

Figure 3. Numerical flume for operational and extreme wave conditions for the baseline layout. In orange the extension of the OCW3D model; in light blue the extension of the OpenFOAM domain. All units are in model scale. Upper figure: OCW3D model coupled with OpenFOAM. Lower figure: zoom in to OpenFOAM domain. In parenthesis the extension of the domain for extreme conditions

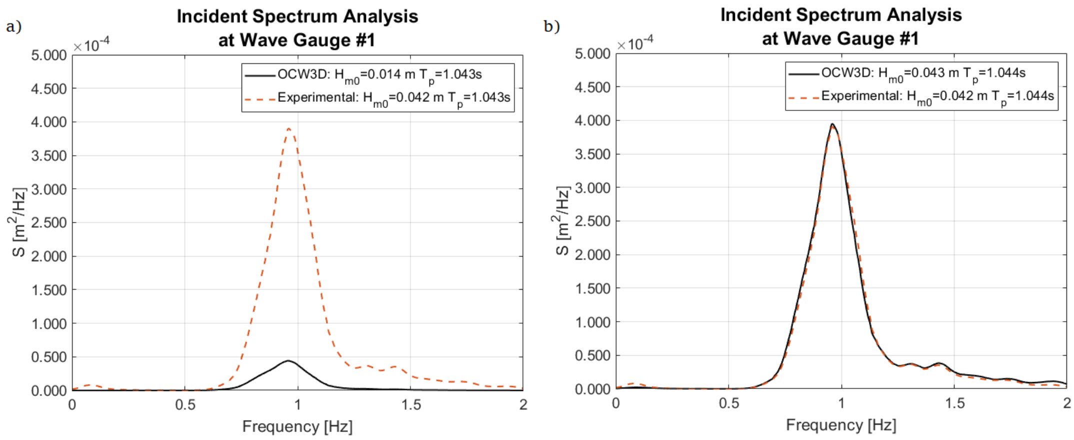

Figure 4. Comparison of incident Spectrum Analysis and water surface elevation at Wave Gauge 1 for operational conditions. a) Linear interpolation of the wave paddle data, b) FFT signal reconstruction of the wave paddle data. The numerical results are extracted from OCW3D domain.

The spatial resolution is detailed for both numerical solvers: OCW3D and OpenFOAM. In the OCW3D domain, for the vertical axis 11 layers were selected for modelling operational conditions and 16 layers, for extreme conditions. In the horizontal direction, the sensitivity analysis revealed the need of 96 cells/wave length under operational conditions and 186 cells/wave length under extreme conditions

In OpenFOAM, a base mesh of 0.01 m in X and Y direction was created using the blockMesh utility. Then, the mesh was refined in the regions where a good estimation of the physical processes is vital using the snappyHexMesh utility, i.e. near the water surface, at the shoaling area, near the slope surface and around the crest wall. For the later region, two levels of refinement were used since high resolution close to the wall is desired for obtaining better prediction of the forces. Antonini et al. (2017), Jacobsen et al. (2018) and Molines et al. (2019) also applied two levels of refinement around the wall. For the other refinement regions, one refinement level was used. The refinement around the water surface and the shoaling area was included to have nearly 9 cells/wave height for operational conditions and to nearly 21 cells/wave height for extreme conditions. In this way, the wave propagation and wave breaking processes are modelled as accurate as possible since they have a direct impact on the forces exerted on the wall. Finally, the refinement near the slope surface was added due to the presence of the boundary layer. The impermeable foreshore and crest wall were removed from the domain with the snappyHexMesh utility. As advised by Jacobsen et al. (2012), square cells were used because they resolve best the non-linear waves. In total, the operational conditions domain consists of approximately 96,652 cells and the extreme conditions domain, of 113,717 cells.

In the numerical flume, the Tetrapods are not modelled by individual pods but by adding a porous layer with specific properties characterized by the parameters: median grain diameter, porosity, closure coefficients α and β and the KC number. The nominal diameter, based on the physical modelling campaign, is 0.08 m and the porosity is set to 0.5, following the recommendations from the Rock Manual (CUR et al., 2007) as it was not measured in the laboratory. Due to the fact that numerical modelling of Tetrapods units is a topic with little available research (Hsu et al., 2002, Neves et al., 2011 and Lee et al., 2019), different combinations of coefficients α and β are tested in the model (α=200, 500 and 1000 and β=0.8, 1.1 and 1.8). As mentioned previously, the KC number incorporates the effect of the non-stationary flow in the nonlinear resistance coefficient *b* in the Darcy-Forchheimer equation. A KC number of 2.19 for operational conditions and 7.41 for extreme conditions was applied in the numerical flume. Since a few researchers (Jacobsen et al., 2018 and Lee et al., 2019) have obtained valid results by excluding the influence of the oscillating flow in the estimation of the nonlinear drag coefficient, a simulation with a KC value of 10,000 is also run to gain more insight into this parameter.

To assess the difference in total force experienced by the crown wall, two methods where applied. The first is placing probes along the vertical axis of the wall to record the pressures, as done in the physical flume. The second method relies on the OpenFOAM capability to record the forces along the entire front face of the wall. The first method is used to compare the wave induced forces between the physical and the numerical flume, since the pressures were recorded at the same locations, while the second method allows to get an overall picture of the forces experienced by the wall.

NUMERICAL MODEL VALIDATION

Four validation cases were used to test the capabilities of the numerical flume for reproducing the water surface elevation and predicting the forces on the front face of the crest wall. Two special settings are analysed in more detail. For the Baseline layout under operational and extreme conditions, the influence of the ventilated boundary condition is studied by varying the degree of openness. For the Tetrapods layout subjected to extreme conditions, a sensitivity analysis of the porous media parameters is carried out. Additionally, the effect of including a simple turbulence model is considered for the Baseline layout under extreme conditions.

The validation procedure consists of the following steps. First, the modelled and measured surface elevation and dynamic pressure time signals are aligned. Second, a reflection analysis applying the method of Zelt and Skjelbreia (1993) is used to decompose the incoming and reflecting waves at the location of wave gauge 10 (2.4 m from the crown wall) using wave gauges 6-10. Then, a comparison of the incoming surface elevation at gauge 10 in bulk wave statistics (H_{m0}, T_p), time domain and frequency spectrum is undertaken. Followed by a time domain comparison of pressures and forces exerted on the wall.

For the sake of comparison, the force was spatially integrated in the physical and numerical flume and both the pressures and forces obtained numerically were resampled to the time step of the experimental data ($\Delta t = 0.005$s) to have the same sampling frequency in the experimental and numerical time series.

Finally, the force events are compared. A force event is a pressure increase experienced by the wall as a result of the impact of a wave or a group of waves. By following this approach, the force events and even more the maximum forces are analyzed rather than the full-time signal because these are the forces required for the proper design of the structure. To select the maximum forces associated to each force event, a peak over threshold (POT) method is followed. In this way, the force events are identified and only the highest value is sort out for each event. The number of force events is not only dependent on the duration of the test but also on the structure itself. To be able to compare different structures (or different numerical settings), the exceedance probabilities are based on the number of incident waves (N_{waves}) reaching the structure during the simulated time frame:

$$P = \frac{r}{N_{waves}+1} \tag{7}$$

Here, *r* is the rank of the sample, once ordered from largest to smallest. The number of incident waves were defined at wave gauge 10, located 2.4 m from the crest wall just before the steep slope of the breakwater. Wave gauge 10 was selected because the wave decomposition method is limited to non-sloping bottom profiles.

RESULTS

The results obtained from the validation and sensitivity studies are exemplified and summarized per case in this section.

Validation case 1: Baseline layout under operational conditions

A time frame of 100 s including 87 waves was simulated in the numerical flume. The ventilated boundary condition was applied to the wall with a degree of openness of 3.0% and a loss coefficient of 1.5, values recommended by Jacobsen et al. (2018).

During this test case, the waves present a behaviour closer to a partially standing wave pattern. The high reflection was induced by the impermeable structures and the non-breaking nature of the waves. Figure 5 shows the incident water surface elevation, recorded in the physical and numerical flume, showing that the model is able to reproduce the wave conditions generated during the physical modelling campaign for a mild wave climate. This fact is reflected in a Pearson correlation coefficient of 0.91. Furthermore, the spectrum analysis indicates that the wave energy at gauge 10 for all frequencies is fairly captured by the numerical flume. Differences of less than 5.0% and 1.5% were found between the modelled and measured significant wave height and peak period, respectively.

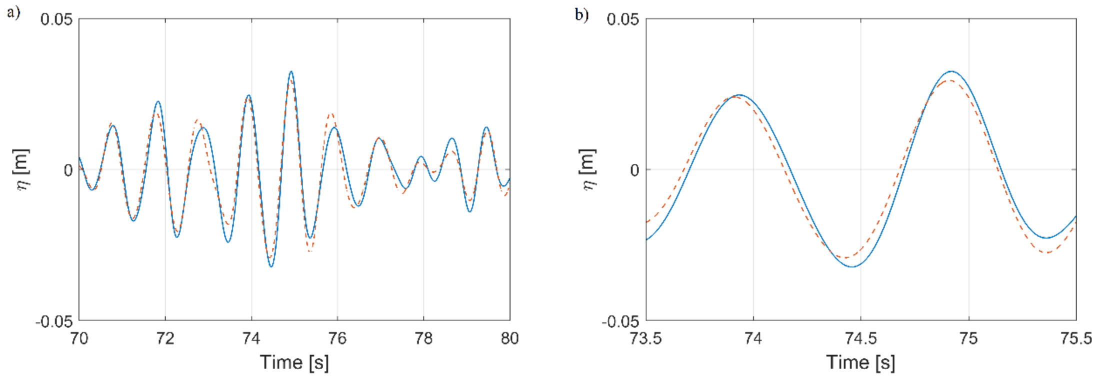

Figure 5. Incident water surface measured at wave gauge 10 located 2.4 m from the front face of the crest wall for the Baseline layout under operational conditions, a) time series of incident waves captured between 70-80 s and b) zoom in of time series of incident waves between 73.5-75.5 s.

An analysis of the pressure sensors timeseries reveals that a better reproduction of the pressures occurs below water level and at still water level than above still water level. This is portrayed with Pearson correlation coefficients above 0.87 for the pressure recordings below still water level and between 0.65 and 0.82 for the pressure recordings above still water level. Around the water level the simulation of the water movement is more complex; nevertheless, since the main pressures exerted by the waves happened below and at the still water level, the overall behaviour of the dynamic forces is well predicted by the numerical model, depicted with a Pearson correlation coefficient of 0.91. The timeseries analysis also shows that along the simulation, underpredictions and overpredictions of wave induced pressures are displayed.

To have an insight into the maximum wave induced pressures and forces, the force events are studied. A comparison between the modelled and measured force events resulted in a RMSE (Root Mean Square Error) of 4.9 N/m and a Pearson correlation coefficient of 0.91. Figure 6a compares statistically the force events captured by the physical and numerical model. Overall, the numerical flume predicts the maximum forces with an average error of 1.3%. For the highest wave induced forces, the numerical flume overpredicts the force by a difference of 32%.

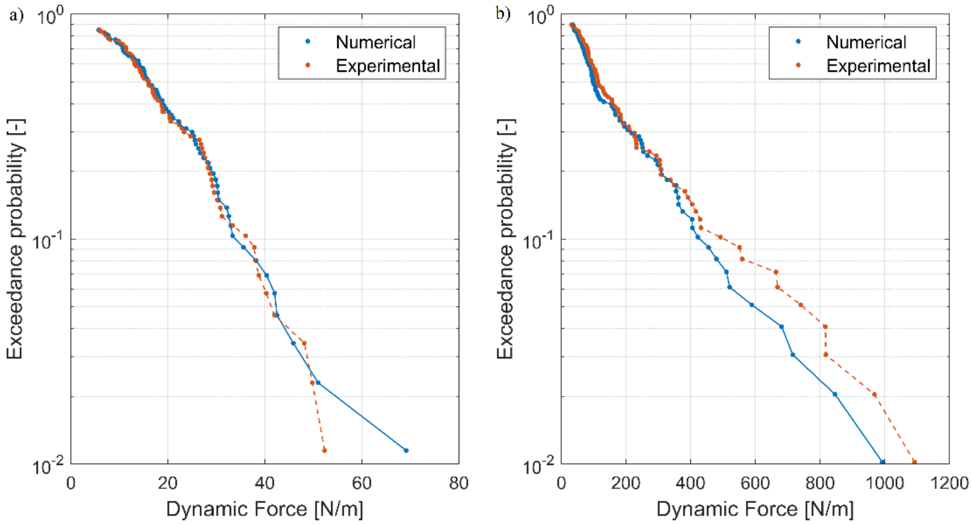

Figure 6. Experimental and numerical exceedance curve comparison. a) Baseline layout under operational conditions, b) Baseline layout under extreme conditions

After checking that the numerical model was able to reproduce the water surface and the forces with sufficient accuracy, a sensitivity analysis of the ventilated boundary condition was conducted by varying the degree of openness of the wall between 0.5% and 6.0%, in order to gain more insight into this newly developed boundary.

The results show that a higher degree of openness, associated with more aeration, results, as expected, in less wave reflection (K_r=0.73). For the case without the ventilated boundary condition, the reflection is highest since no aeration is present through the concrete wall. This was confirmed by the numerical flume, with a total reflection of the incident wave field. Regarding the wave induced forces, there is not a significant difference in the outcome of OpenFOAM when the full time series are analysed (overall correlations above 0.90). When comparing event by event (see exceedance curves in Figure 7a), the results from the numerical flume are not that sensible to variations in the degree of openness of the wall. For all the simulations, correlations above 0.88 and RMSE below 6 N/m are obtained. Given these results, no recommendation can be drawn for the value of the degree of openness when the breakwater is subjected to normal conditions. By using any value for the degree of openness or even by excluding this boundary condition, a numerical model with enough accuracy is obtained.

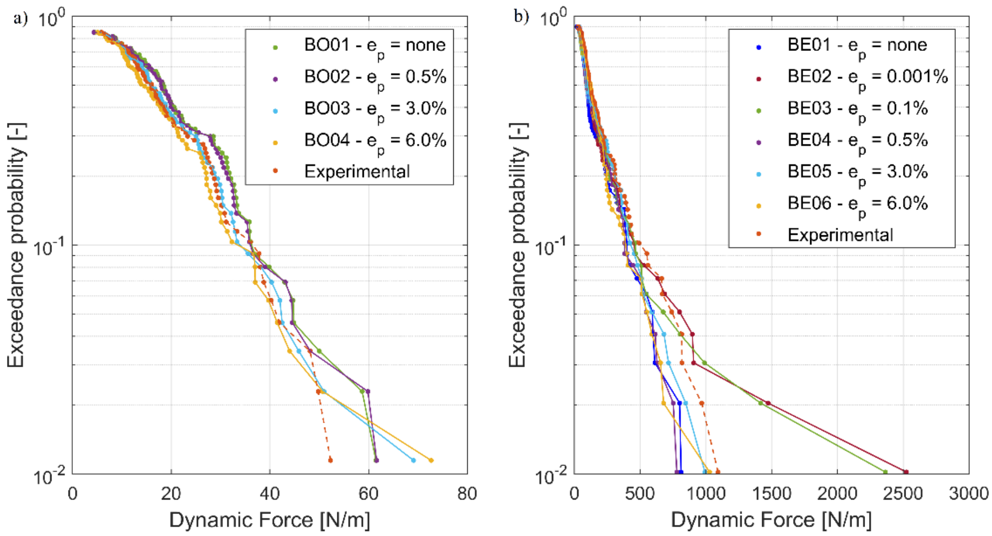

Figure 7. Experimental and numerical exceedance curves comparison for various degrees of openness. a) Baseline layout under operational conditions, b) Baseline layout under extreme conditions

Validation case 2: Baseline layout under extreme conditions

A time frame of 150 s including 98 waves was simulated. The ventilated boundary condition was applied to the wall with a degree of openness of 3.0% and a loss coefficient of 1.5.

In this extreme scenario, due to a higher value of H_{m0} and T_p, partially standing waves, slightly breaking waves, heavily breaking waves and already broken waves hit the structure. The comparison between the incident water surface elevation, recorded in the physical and numerical flume proves that the overall shape of the time signal can be fairly reproduced by the numerical flume, reflected in a Pearson correlation coefficient of 0.92. Looking at the bulk wave statistics, differences of less than 3.0% and 1.5% were found for the significant wave height and peak period, respectively. In this validation case there is an underestimation of the wave energy for waves with frequencies above 0.8 Hz. It appears that the number of cells/wave length is not sufficient to resolve the high frequency waves in the numerical model for an extreme wave climate. This happened because the mesh optimization process focused on representing properly the highest waves.

The correlations between the pressure sensors timeseries exhibit the same behaviour as in the operational conditions, i.e., the pressure sensors located below still water level have higher correlations than the pressure sensors above still water level. Again, the farthest the sensor is from the still water level, the harder is to predict the wave impact by the numerical flume. For extreme conditions, the numerical predictability of the dynamic forcing lowers to a correlation of 0.71.

The modelled and measured force events are compared. For this validation case, a RMSE of 215.81 N/m and a Pearson correlation coefficient of 0.45 are obtained. There is a notable decrease in accuracy compared to the operational conditions simulation. A statistically comparison is shown in Figure 6b. For these specific settings, the numerical flume usually underpredicts the wave induced forces. For the forces above 400 N/m, the underprediction has an error, in average, of 14%.

Under heavily breaking waves, the influence of the ventilated boundary condition and different degrees of openness was also studied. The degree of openness of the ventilated boundary condition was changed between 0.001% and 6.0%. Besides, a simulation excluding the ventilated boundary condition was also executed. In line with the results obtained for the normal conditions, more aeration through the wall implies less wave reflection. Regarding the wave induced forces, correlations above 0.65 are obtained for the dynamic forces timeseries. Thus, there is a clear decrease in accuracy when modelling heavily breaking waves in the numerical flume.

Under this wave climate, unlike under operational conditions, there is a notable influence of the degree of openness on the forces predictability (see exceedance curves in Figure 7b). It is noted that a lower ventilation through the wall results in more entrapped air, thus, higher forces exerted against the crest wall. The simulation performed with 0.5% of openness and the simulation without the ventilated boundary condition display an outlier behaviour. For the later, it was expected that the associated force events were higher since no ventilation is given in the numerical flume. Nonetheless, its behaviour resembles more the numerical simulation with the 6.0% degree of openness (Simulation BE06). The best resemblance is obtained with a degree of openness of 3.0% (Simulation BE05), which is the same result as Jacobsen et al. (2018).

Validation case 3: Tetrapods layout under operational conditions

A time frame of 100 s including 87 waves was simulated in the numerical flume with the following porous media parameters (α = 200, β = 1.1 and KC = 2.187) and a degree of openness of 3.0% for the ventilated boundary condition.

During this test, due to the presence of the Tetrapods layer in front of the crest wall, a different wave pattern is exhibit. Now, under operational conditions, there is wave damping and wave breaking. The analysis of the time signals of incident surface elevation measured in both models reveals a good agreement, reflected in a Pearson correlation coefficient of 0.91. A close look to the spectrum analysis indicates that the wave energy for all frequencies is fairly captured by the numerical flume. There is a slight overestimation of wave energy, for frequencies above 0.8 Hz. However, the discrepancies are not very relevant since differences of less than 3.0% and 1.5% were found for the significant wave height and peak period, respectively.

A comparison between the time signals of the wave induced pressures and forces measured in the physical and numerical flume reveals that the numerical model is capable of predicting the behaviour of the dynamic forces subjected to normal conditions, when a porous media layer is included in the numerical flume. This is portrayed by a Pearson correlation coefficient of 0.87 for the dynamic forces. The event by event comparison between the modelled and measured force events returned a RMSE of

5.96 N/m and a Pearson correlation coefficient of 0.85. The statistically force events comparison is presented in Figure 8a. The comparison reveals that using these numerical settings, the numerical model underpredicts the maximum forces below 40 N/m and overpredicts the maximum forces above 40 N/m. For the largest dynamic force, the difference in prediction is around 1.5%.

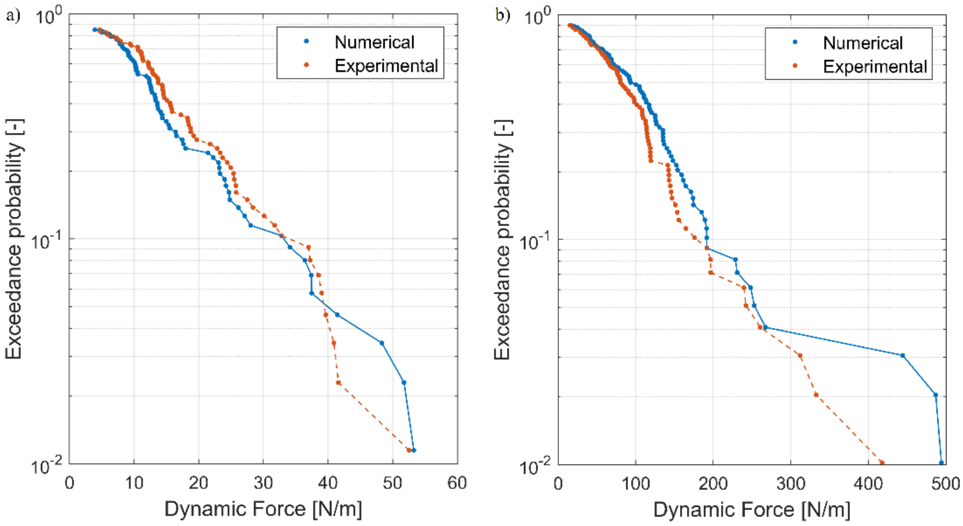

Figure 8. Experimental and numerical exceedance curve comparison. a) Tetrapods layout under operational conditions, b) Tetrapods layout under extreme conditions

Validation case 4: Tetrapods layout under extreme conditions

A time frame of 150 seconds with a total of 98 waves was used in the numerical flume with the following porous media parameters ($\alpha = 200$, $\beta = 1.1$ and KC = 7.407) and a degree of openness of 3.0% for the ventilated boundary condition.

In this validation case, heavily breaking waves reaching a partly-permeable breakwater conformed by a Tetrapods layer were simulated. The results show again a good agreement between the time series of the incident waves recorded in the physical and numerical flume, which is reflected in a correlation coefficient of 0.91. Analysing the bulk hydrodynamics indicate differences of less than 1.0% and 2.5% for the significant wave height and peak period, respectively. Thus, the energy distribution is well-captured by the numerical model.

Under heavily breaking waves and under the presence of a porous media layer, the numerical predictability of the dynamic forcing displays correlations of about 0.70. The event by event comparison between the modelled and measured force events returned a RMSE of 81.93 N/m and a Pearson correlation coefficient of 0.51. By comparing the force events statistically (see exceedance curves in Figure 8b), it is noted that using these numerical settings, the numerical model overpredicts the maximum forces. For the largest dynamic force, the difference in prediction is around 18%.

For this validation case the influence of the combined porous media drag coefficients on the resulting forces exerted on the wall is studied. For this purpose, a total of six simulations were run, where α, β and KC were varied. The parameter α, associated to laminar flow inside the skeleton, was changed between 200 and 1000, while the parameter β, associated to turbulent flow inside the skeleton, between 0.8 and 1.8. Therefore, simulations TT02, TT04 and TT05 focus on the importance of laminar flow inside the Tetrapods layer. On the other hand, simulations TT01, TT02 and TT03, on the importance of turbulent flow. The oscillatory flow, accounted in the KC number, was calculated as 7.41 for extreme conditions. Simulation TT06 uses a KC of 10,000; removing the influence of the oscillatory movement in the porous media drag coefficients.

There are no significant differences in the incident wave attack for the different test cases. Moreover, the results indicate that no trend can be inferred between the linear and nonlinear drag coefficients and the reflection coefficient. The results also show that the numerical flume is able to reproduce the shape and the order of magnitude of dynamic forces (reflected in time signal correlation coefficients of 0.70-0.74). Small deviations were encountered in the exact time of the maximum force, which do not have a large influence in the design process. Finally, the force events are studied. Despite the different parameters combination, all the numerical results are predicted within a 50% of error; being the error largest for the highest forces. The exceedance curves (see Figure 9) indicate that the best fit is obtained from Simulation TT05 (α = 1,000, β = 1.1 and KC = 7.407). This set of coefficients have the same values recommended by Van Gent (1995a,b) for a rock layer. Finally, the effect of including or excluding the effect of the oscillatory flow was studied in Simulations TT05 (α = 1000, β = 1.1 and KC = 7.407) and TT06 (α = 1,000, β = 1.1 and KC = 10,000). By setting KC to 10,000, the contribution of the oscillatory flow is neglected. By excluding this contribution, the reproduction error of the largest force increased from 1.0% to 12%.

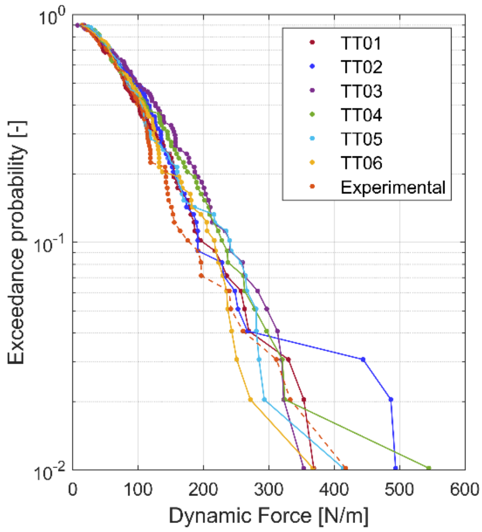

Figure 9. Experimental and numerical exceedance curves comparison various combinations of porous media parameters for the Tetrapods layout under extreme conditions

Turbulence modelling

So far, all the presented results were obtained based on simulations where no turbulence model was included. The common belief is that a turbulence model becomes more relevant when heavily breaking waves are present in the numerical flume and no energy dissipation is happening inside a porous media layer, i.e. validation case 2. To study its importance, a simple constant eddy viscosity model with an eddy viscosity of 10^{-3} was applied to the simulation BE05. Figure 10 compares the numerical simulations against the experimental maximum dynamic forces. For the settings applied in the numerical model, not including a turbulence model provides a better agreement with the physical test results. This result along the other simulations developed during this research allowed to determine that for practical applications it is not essential to include a turbulence model in the numerical flume to obtain reliable forces on the front face of crest walls on top of composite breakwaters subjected to non-breaking and heavily breaking waves. Other researchers (Jensen et al., 2014, Jacobsen et al., 2018) already reached to this conclusion when there is little energy dissipation caused by wave breaking and when there is large energy dissipation caused by high levels of turbulence inside a porous media. Now, the results from this investigation allow to extend the validity of not including a turbulence model in the numerical flume, for the cases when there is no energy dissipation inside a porous media but there is large wave breaking dissipation (i.e. validation case 2). The validity of not including a turbulence model in the numerical flume may be explained by the fact that the numerical dissipation in OpenFOAM is enough to mimic the physical dissipation caused by the wave breaking in the surf zone. Nevertheless, further research should be undertaken to validate this assumption.

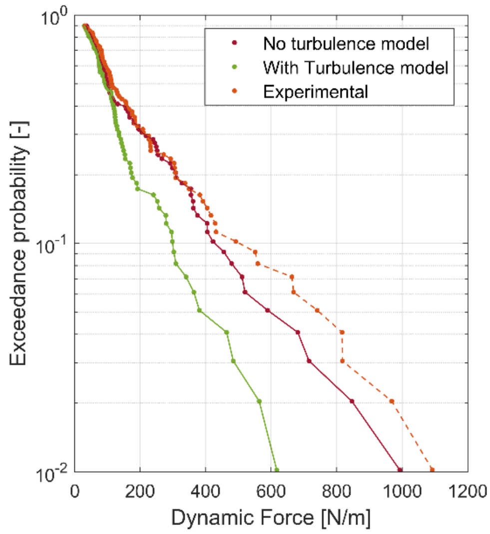

Figure 10. Experimental and numerical exceedance curves comparison between simulations including and excluding a turbulence model

CONCLUSIONS

The purpose of the current study was to determine the capability of the OpenFOAM model to accurately estimate the forces on the front face of crest walls on top of composite breakwaters subjected to non-breaking and heavily breaking waves. The assessment was based on the Holyhead breakwater located in Wales. Four physical tests have been used to validate the 2DV OpenFOAM model. Sensitivity analysis of the degree of openness of the ventilated boundary condition and of the porous media parameters for layers conformed by Tetrapods were performed. The results obtained from the numerical flume made it possible to draw the following conclusions:

- The numerical model is able to reproduce the wave conditions generated during the physical modelling campaign ($\rho \geq 90\%$ for all the simulations).
- The numerical model is able to reproduce with some degree of accuracy the time series of wave induced forces ($\rho \geq 65\%$ for all the simulations).
- The ventilated boundary condition improves the numerical prediction of the maximum wave induced forces based on exceedance curves, under heavy wave attack. The reason behind it is that some air ventilation is required in the interface between water surface and structural elements to mimic accordingly the air-water mixture when the structure is subjected to breaking waves.
- The inclusion of the ventilated boundary condition is not necessary under non-breaking waves due to the lack of air entrapment, although its inclusion does not pose inaccuracies in the wave induced forces.
- Based on the sensitivity analysis, a degree of openness of 3.0%, α = 1,000, β = 1.1 and adding the contribution of the oscillatory flow inside the porous layer conformed by Tetrapods are recommended. These are the default settings for the first three parameters (ep, α and β) .
- For practical applications it is not essential to include a turbulence model in the numerical flume to obtain reliable forces on the front face of crest walls on top of impermeable and partly-permeable breakwaters subjected to non-breaking and heavily breaking waves. This conclusion was already drawn by other researchers (Jensen et al., 2014, Jacobsen et al., 2018) when the main source of energy dissipation happened inside a porous media layer. By including an impermeable breakwater and heavily breaking waves in the numerical flume, where the main source of energy dissipation is now related to the breaking process, the exclusion of a turbulence model can be generalized.
- In the numerical flume, more information about the wave induced pressures and forces can be obtained by placing more pressure transducers or by using the patch method that allows to obtain the forces and moments along the entire front face of the crest wall. Therefore, a better picture of the forces and pressure distribution in the front face can be obtained.

REFERENCES

Antonini, A., Archetti, R., and Lamberti, A. 2017. Wave simulation for the design of an innovative quay wall: the case of Vlorë Harbour, *Nat. Hazards Earth Syst. Sci.*, 17, 127–142, https://doi.org/10.5194/nhess-17-127-2017

Berberović, E., van Hinsberg, N., Jakirlić, S., Roisman, I., and Tropea, C. 2009. Drop impact onto a liquid layer of finite thickness: Dynamics of the cavity evolution, *American Physical Society*, 79 (3), 15, https://doi.org/10.1103/PhysRevE.79.036306

Boersen, S., Scholl, O., Jacobsen, N., and van der Lem, C. 2019. Applying a numerical wave flume to predict wave overtopping, *Proceedings of the 38th IAHR World Congress*, https://doi.org/10.3850/38WC092019-1337

Brown, S., Greaves, D., Magar, V., and Conley, D. 2016. Evaluation of turbulence closure models under spilling and plunging breakers in the surf zone, *Coastal Engineering*, 114, 177–193, https://doi.org/10.1016/j.coastaleng.2016.04.002

Castellino, M., Romano, A., Lara, J.L., Losada I.J., and Girolamo, P. 2021. Confined-crest impact: Forces dimensional analysis and extension of the Goda's formulae to recurved parapets, *Coastal Engineering*, 163, https://doi.org/10.1016/j.coastaleng.2020.103814

Chen, W., Warmink, J.J., van Gent, M.R.A., and Hulscher, S.J.M.H. 2021. Numerical modelling of wave overtopping at dikes using OpenFOAM®, *Coastal Engineering*, 166, https://doi.org/10.1016/j.coastaleng.2021.103890

CUR, CIRIA, and CETMEF. 2007. Rock Manual, The use of rock in hydraulic engineering (Second ed.). London.

Devolder, B. 2018. Hydrodynamic Modelling of Wave Energy Converter Arrays, Ph.D. Thesis, Ghent University and KU Leuven.

DHI. 2019. 11824034 Holyhead Breakwater 2D Physical Model Test Report, Technical Report.

Engsig-Karup, A. P., Bingham, H., and Lindberg, O. 2009. An efficient flexible-order model for 3D non-linear water waves, *Journal of Computational Physics*, 228 (6), 2100–2118, https://doi.org/10.1016/j.jcp.2008.11.028

Hsu, T.-J., Sakakiyama, T., and Liu, P. L.-F. 2002. A numerical model for wave motions and turbulence flows in front of a composite breakwater, *Coastal Engineering*, 46 (1), 25–50, https://doi.org/10.1016/S0378-3839(02)00045-5

Irías Mata, M., and van Gent, M.R.A. 2023. Numerical modelling of wave overtopping discharges at rubble mound breakwaters using OpenFOAM®, *Coastal Engineering*; https://doi.org/10.1016/j.coastaleng.2022.104274

Jacobsen, N., Fuhrman, D., and Fredsøe, J. 2012. A wave generation toolbox for the open-source CFD library: OpenFoam®. *International Journal for Numerical Methods in Fluids*, 70 (9), 1073–1088, https://doi.org/10.1002/fld.2726

Jacobsen, N., van Gent, M.R.A., and Wolters, G. 2015. Numerical analysis of the interaction of irregular waves with two dimensional permeable coastal structures, *Coastal Engineering*; 102, 13–29, https://doi.org/10.1016/j.coastaleng.2015.05.004

Jacobsen, N., van Gent, M.R.A., and Fredsøe, J. 2017. Numerical modelling of the erosion and deposition of sand inside a filter layer, *Coastal Engineering,* 120, 47–63, https://doi.org/10.1016/j.coastaleng.2016.09.003.

Jacobsen, N., van Gent, M.R.A., Capel, A., and Borsboom, M. 2018. Numerical prediction of wave loads on crest walls on top of rubble mound structures, *Coastal Engineering*, 142, 110–124, https://doi.org/10.1016/j.coastaleng.2018.10.004

Jensen, B., Jacobsen, N., and Christensen, E. D. 2014. Investigations on the porous media equations and resistance coefficients for coastal structures, *Coastal Engineering*, 84, 56–72, https://doi.org/10.1016/j.coastaleng.2013.11.004

Karagiannis, N., Karambas, T., and Koutitas, C. 2015. Wave overtopping numerical simulation using OpenFoam, *E-Proceeding of the 36th IAHR world congress*.

Larsen, B. E., and Fuhrman, D. R. 2018. On the over-production of turbulence beneath surface waves in Reynolds-Averaged Navier–Stokes models, *Journal of Fluid Mechanics*, 853, 419–460. https://doi.org/10.1017/jfm.2018.577

Lee, G. S., Oh, S.-H., and Yoon, S. B. 2019. Evaluation of Empirical Porous-Media Parameters for Numerical Simulation of Wave Pressure on Caisson Breakwater Armored with Tetrapods, *Journal of Korean Society of Coastal and Ocean Engineers,* 31 (6), 344–350. https://doi.org/10.9765/KSCOE.2019.31.6.344

Molines, J., Bayon, A., Gómez-Martín, M.E., and Medina, J.R. 2019. Influence of parapets on wave overtopping on mound breakwaters with crown walls, *Sustainability*, 11, 7109, https://doi.org/10.3390/su11247109

Neves, M. G., Reis, M. T., Gadelho, J. F., Lara, J. L., Pinto, F. T., Lopes, H. G., and Cabral, J. P. 2011. Numerical modelling of waves interacting with the breakwaters of Leixões harbour, Portugal, *International Conference on Computational Methods in Marine Engineering MARINE 2011*.

Nørgaard, J. Q. H., Andersen, T. L., and Burcharth, H. F. 2013. Wave loads on rubble mound breakwater crown walls in deep and shallow water wave conditions, *Coastal Engineering*, 80, 137–147. https://doi.org/10.1016/j.coastaleng.2013.06.003

Paulsen, B. T., Bingham, H. B., and Bredmose, H. 2013. Efficient computations of wave loads on offshore structures, PhD Thesis, Technical University of Denmark.

Pedersen, J. 1996. Wave Forces and Overtopping on Crown Walls of Rubble Mound Breakwaters, Ph.D. Thesis, Aalborg University.

Ramachandran, K., Schimmels, S., Stagonas, D., and Müller, G. 2013. Measuring Wave Impact on Coastal Structures with High Spatial and Temporal Resolution – Tactile Pressure Sensors a Novel Approach, *Proceedings of 2013 IAHR Congress*.

Van Gent, M.R.A., Tonjes, P., Petit, H.A.H., and van den Bosch, P. 1994. Wave action on and in permeable structures, *Coastal Engineering Proceedings*, https://doi.org/10.9753/icce.v24.%25p

Van Gent, M.R.A. 1995a. Wave interaction with permeable coastal structures. Ph.D. Thesis, TU Delft, ISBN 90-407-1182-8, Delft University Press.

Van Gent, M.R.A. 1995b. Porous flow though rubble mound material, *Journal of Waterway, Port, Coastal and Ocean Engineering*. 121 (3), 176-181.

Van Gent, M.R.A., Jacobsen, N., and Wolters, G. 2018. Modelling of open filters under wave loading. *Proceedings Coasts, Marine Structures and Breakwaters 2017*. https://doi.org/10.1680/cmsb.63174.1081

Weller, H. G., Tabor, G., Jasak, H., and Fureby, C. 1998. A tensorial approach to computational continuum mechanics using object-oriented techniques. *Computers in Physics*, 12 (6), 620, https://doi.org/10.1063/1.168744

Zelt, J., and Skjelbreia, J. E. 1993. Estimating Incident and Reflected Wave Fields Using an Arbitrary Number of Wave Gauges, *Coastal Engineering Proceedings,* 1(23), https://doi.org/10.1061/9780872629332.058