NUMERICAL SIMULATION OF WAVE OVERTOPPING AT DIKES

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The average overtopping discharge is an important parameter for the design of flood defences. Several empirical formulas are available for predicting the overtopping discharge at dikes. However, these empirical formulas often have their specific applicable conditions. To complement with the empirical methods, a numerical model has been developed using the open source CFD package OpenFOAM to model the wave overtopping at dikes. Systematic calibration and validation of the numerical model are performed. The influences of the mesh, solver, turbulence model and roughness height on the modelled results of the average overtopping discharge have been investigated during the model calibration. The simulations show that the turbulence model increases the accuracy of the numerical model for predicting the average overtopping discharge under wave breaking conditions. The calibrated model is then validated by comparing the modelled average overtopping discharges with the measured ones from the physical model tests. Results show that the OpenFOAM model is capable of predicting the average overtopping discharge accurately at dikes that have a smooth straight waterside slope.

Keywords: OpenFOAM; average overtopping discharge; waves2Foam; numerical model; coastal structures

INTRODUCTION

The risk of wave overtopping at a dike is increasing nowadays due to increased loads caused by a combination of climate change, sea level rise and land subsidence. Wave overtopping over a dike during a storm surge event can cause significant damage to the dike, which might lead to flooding, loss of lifes and damage to the infrastructure in the hinterland. The average overtopping discharge is a key element in determining the crest elevation and the geometry of the waterside slope of a dike in practice, making sure that the average overtopping discharge is reduced to acceptable levels.

Several empirical methods (e.g., TAW, 2002; EurOtop, 2018; Chen et al., 2020a; Chen et al., 2020b) are available for predicting the overtopping discharges at dikes. These empirical equations have been used to calculate the average overtopping discharges during the last decades. However, there is a wide range of structure configurations and wave conditions in practice. The empirical equations often have their specific applicable conditions and therefore it is uncertain whether they are also applicable for the conditions that are outside of the applicable ranges of the empirical equations. With the development of numerical methods and computational resources, numerical modelling has become an important complementary tool with empirical formulas for design of coastal structures (Jensen et al., 2014). OpenFOAM is an open-source computational fluid dynamics framework which is applied in many fields of aero- and hydrodynamics. Due to the open-source nature, many useful libraries and toolboxes are freely shared in the public domain (Davidson et al., 2015), which makes the OpenFOAM library becoming increasingly popular in the field of coastal engineering.

There has been a variety of research on numerical modelling of wave overtopping discharge at coastal structures using OpenFOAM. Instantaneous wave overtopping discharge over a porous coastal structure was simulated in three dimensions by Higuera et al. (2014b). However, the model results of overtopping discharges were not validated with the experimental results. Besides, the 3D simulation is quite computationally expensive, only a total of 40s was simulated for overtopping, which is less sufficient for a reliable estimation of average overtopping discharge. Waves2Foam developed by Jacobsen et al. (2012) based on the framework OpenFOAM is becoming popular in simulating wave-structure interactions. The waves2Foam is a toolbox that can be used to generate and absorb free surface water waves. Jensen et al. (2014) applied waves2Foam to model the wave overtopping over a smooth straight slope and over a porous breakwater. The 2DV model developed in Jensen et al. (2014) was found to give a good agreement between the simulated and measured average overtopping discharges. Since not too much wave breaking was present during the physical model tests, no turbulence model was applied to account for the turbulence influence in the numerical model, which indicates that the applicability of the model might be limited to non-breaking conditions. Patil (2019) also used wave2Foam to simulate the average overtopping discharge at an impermeable dike that has a smooth straight waterside slope. There was a good agreement between modelled and measured results while the overtopping discharge was slightly underestimated by the numerical model. Besides, only one case was simulated for the wave overtopping discharge.

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From the above, even though some research has been conducted on the simulation of wave overtopping using OpenFOAM, detailed and systematic calibration and validation of the OpenFOAM model for simulating the wave overtopping discharge at dikes still lack. Therefore, this study aims to explore the capability of the OpenFOAM in predicting the overtopping discharges over dikes by providing a systematic calibration and validation of the numerical model. A 2DV numerical model is set up in this paper using waves2Foam to simulate the overtopping process with respect to irregular waves at a dike. Physical model tests on the overtopping over a smooth straight slope from Chen et al. (2020a) are used to calibrate and validate the numerical model. One physical model test is selected to calibrate the OpenFOAM model by adjusting the mesh size, solvers, turbulence models and roughness heights. The calibrated model settings are then validated by using 8 physical model tests. For the model calibration, each simulation runs for 250s corresponding to nearly 140 waves to save computing time. As for the model validation, simulations run for 500s equivalent to 250 ~ 350 waves depending on the wave period and so this simulation time is sufficient to obtain reliable estimations of the average overtopping discharge in this study.

NUMERICAL SET-UP

Experiments

Experiments performed by Chen et al. (2020a) are used to calibrate and validate the 2DV OpenFOAM model. A detailed description on the experiments can be found in Chen et al. (2020a). A brief introduction of the physical model tests that are used to calibrate and validate the numerical model is given in the following. These experiments were performed in the Pacific Basin at Deltares in the Netherlands. The basin is 18.6 m long, 14 m wide and 1.25 m deep. The tested model was placed at a distance of 11 m from the wave board. The structure with a smooth straight waterside slope as shown in Figure 1 was considered in this paper. The structure was impermeable and was made of concrete. A slope of 1:3 was used for the straight slope. Three wave gauges were placed near the toe of the structure to measure the wave conditions. The incident and reflected waves were separated using the method developed by Mansard and Funke (1980). The significant wave height (H_{m0}) and the wave period ($T_{m-1,0}$) were varied among different tests. Three water depths h were adopted, given as 0.57 m, 0.60 m and 0.63 m. Overtopping discharges were measured by detecting water surface variation using a wave gauge installed in the overtopping tank. One test (SS1 as presented in Table 1) with the wave condition of $H_{m0} = 0.123$ m, $T_{m-1,0} = 1.72$ s and $h = 0.6$ was selected for calibrating the numerical model. Eight tests (SS2~SS9) which are listed in Table 1 were used to validate the OpenFOAM model.

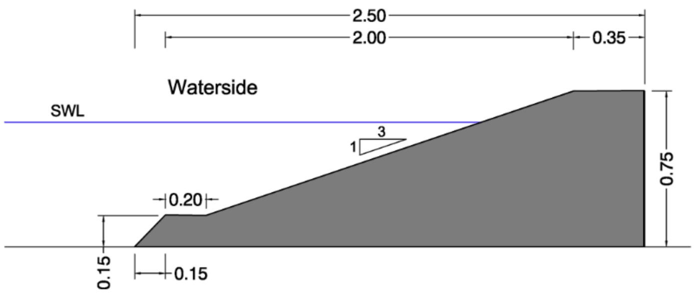

Figure 1. Cross-section of the smooth straight slope where SWL was varied between 0.57 m and 0.63 m (unit: m).

Table 1. Experimental wave conditions for the calibration and validation of the numerical model.

case name	H_{m0} [m]	$T_{m-1,0}$ [s]	$s_{m-1,0}$ [-]	h [m]	simulating time [s]
SS1	0.122	1.72	0.027	0.6	250
SS2	0.115	1.64	0.027	0.6	500
SS3	0.107	1.56	0.028	0.6	500
SS4	0.128	1.69	0.029	0.63	500
SS5	0.099	1.27	0.039	0.57	500
SS6	0.12	1.32	0.044	0.6	500
SS7	0.116	1.23	0.049	0.6	500
SS8	0.127	1.49	0.037	0.6	500
SS9	0.122	1.41	0.039	0.6	500

Numerical set-up

Figure 2 shows the general layout of the 2DV numerical model. The total numerical domain was 17 m long and 1.2 m high. The length of the inlet relaxation zone, which is responsible for generating waves and absorbing reflected waves from the dike structure, was about one wavelength. The focus of this study is on the overtopping discharge and the wave motion behind the structure has no influence on the average overtopping discharge. Therefore, the length of outlet relaxation zone was shorter than one wave length to save the computing time. Waves are generated by importing steering files from experiments to OceanWave3D, which then provides inputs for waves2Foam. OceanWave3D is a flexible-order finite difference model developed based on a potential flow model (Engsig-Karup et al., 2009), which has been coupled with waves2Foam by Paulsen et al. (2014). The instantaneous overtopping flux through a set of faces selected at the landward edge of the crest was extracted using the overtopping utility provided by waves2Foam, in which way the accumulated overtopping volume and the average overtopping discharge can be calculated.

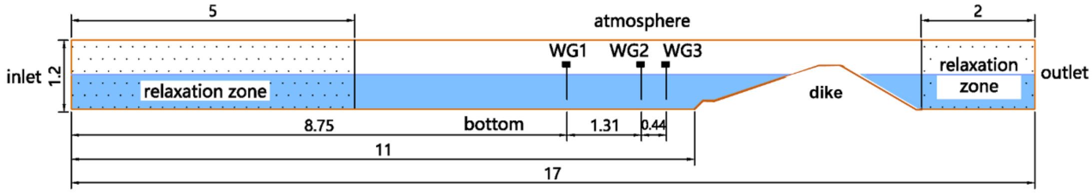

Figure 2. Layout of the numerical wave tank (unit: m).

The background mesh was created using blockMesh. The mesh near the structure was oriented parallel with the slope surface (see Figure 3). The mesh near the free surface was refined using snappyHexMesh in order to model the wave propagation more accurately. Three grid sizes, i.e. coarse mesh of 0.04 m × 0.04 m (0.02 m × 0.2 m for the refinement region near the free surface), medium mesh of 0.02 m × 0.02 m (0.01 m × 0.1 m for the refinement region near the free surface) and fine mesh of 0.01 m × 0.01 m (0.005 m × 0.005 m for the refinement region near the free surface) were considered to check the influence of grid size on the overtopping discharge. There are two solvers included in the waves2Foam that are often used to solve the model for interactions between waves and impermeable structures, i.e. waveFoam and waveIsoFoam. The performance of these two solvers on simulating overtopping events at dikes was compared. Turbulence plays an important role in case of wave breaking. Laminar, the stabilized $k-\omega$ model and the stabilized $k-\omega$ SST model improved by Larsen and Fuhrman (2018) were tested to show the effect of the turbulence model on the modelled results of overtopping discharge. In the turbulence models, the wall functions were applied in the boundary layer avoiding resolving the boundary, which can save computational time. Due to the application of wall functions, the distance of the centroid of the cell nearest the wall to the wall surface was about 0.0022 m ensuring the centroid of the first grid near the wall located in the log layer. The value of the Nikuradse roughness height K_s for smooth surface was calibrated between 0.0001 m and 0.001 m. Nine simulations were performed for calibration and each simulation ran for 250s. During the calibration, the modelled time history of accumulated overtopping volume was compared with the measured result from the experiments. The numerical model was validated by comparing the modelled average overtopping discharges with the experimental ones. The simulations for validating the numerical model ran for 500 s to obtain reliable results of average overtopping discharges.

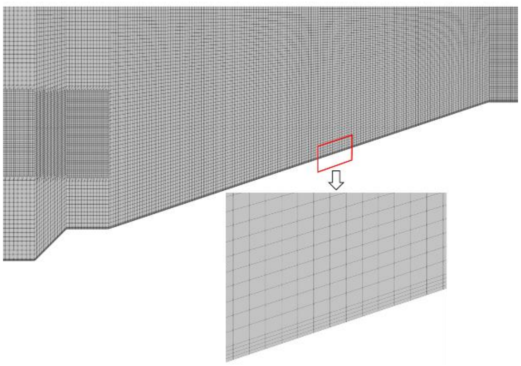

Figure 3. Mesh near the waterside slope and boundary grids near the slope surface.

MODEL CALIBRATION

An accurate simulation of incident waves is essential for modelling the overtopping discharge accurately. Therefore, the accuracy of the incident waves given by the numerical model was investigated first. Different numerical model settings like the grid size and solver could result in different significant wave height while these settings have limited influence on the wave period. Therefore, the steering file for the wave condition of $H_{m0} = 0.123$ m, $T_{m-1,0} = 1.72$ s and $h = 0.8$ m was adjusted using an amplification factor to ensure the incident waves were almost the same for each simulation. Figure 4 shows the modelled and experimental results of time series of incident wave height ($H_{m0} = 0.123$ m, $T_{m-1,0} = 1.72$ s and $h = 0.8$ m) using the medium grid size, waveIsoFoam and $k - \omega$ model. The time series of incident wave height was separated based on the time series of free surface elevation of 0s ~250 s measured by WG1, WG2 and WG3 using the method given by Mansard and Funke (1980) for both numerical model and physical model tests. The wave energy spectra of incident waves given by the numerical model and the physical model test are shown in Figure 5. A good agreement between modelled and measured results can be found in both Figure 4 and Figure 5. The modelled significant wave height H_{m0-OF} is 0.124m and the modelled wave period $T_{m-1,0-OF}$ is 1.78s, which matches well with the measured wave properties.

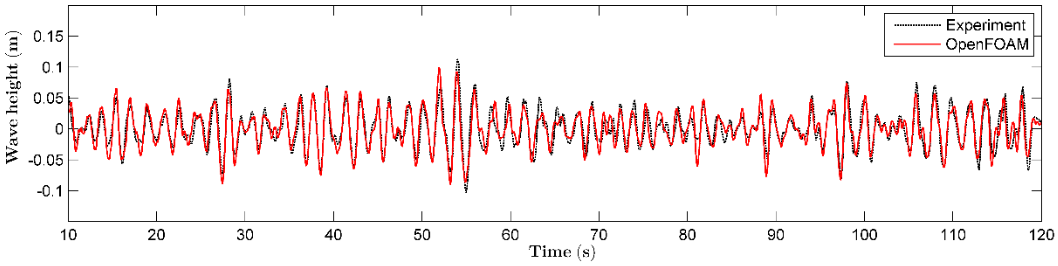

Figure 4. Comparison between the numerical and experimental time series of incident wave height ($H_{m0} = 0.123$ m, $T_{m-1,0} = 1.72$ s and $h = 0.8$ m).

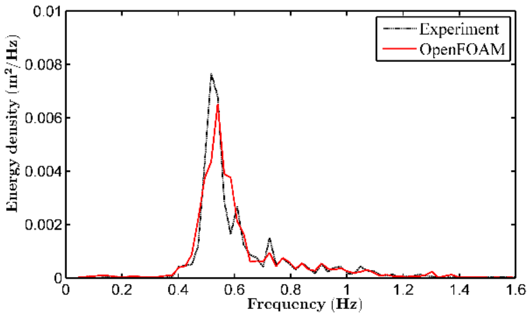

Figure 5. Comparison between the numerical and experimental wave energy spectrum of incident waves ($H_{m0} = 0.123$ m, $T_{m-1,0} = 1.72$ s and $h = 0.8$ m).

Mesh

The coarse grid size of 0.04 m × 0.04 m, medium grid size of 0.02 m × 0.02 m and fine grid size of 0.01 m × 0.01 m were considered. The grid size in the refinement region near the water surface was half of the background gird size. Figure 6 presents the measured and modelled time series of cumulative overtopping volume per meter width with different grid sizes. The model settings were the same except the gird size for these three simulations. No turbulence model was applied and the solver waveFoam was used to solve the model.

Figure 6 shows that as the grid size becomes smaller the modelled result of overtopping volume gets more close to the experimental result. Since the overtopping flow layer along the waterside slope and crest was thin, the water surface can get smeared over the coarse cells resulting in the overestimation of the overtopping flux. Refining the mesh could improve the capture of the water surface thereby improving the prediction of the overtopping flux. It took nearly 1.5 days to finish one simulation of 250s with the coarse mesh using 3 processors (3.6 GHz). The simulation with the medium mesh took 3 days while the simulation with the fine mesh took about 12 days which was more computationally expensive.

Therefore, the medium was adopted in the following simulations to achieve a balance between the model accuracy and the computational time. It is worth noting that the numerical model even with the fine mesh significantly overestimated the overtopping volume. The numerical model requires further improvement.

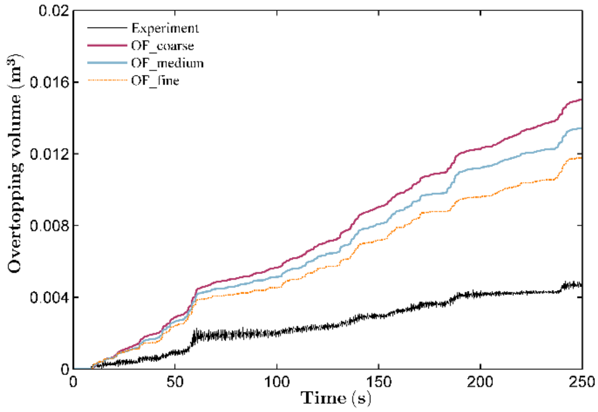

Figure 6. Time series of cumulative overtopping volume per meter width with different grid sizes.

Solver

Using the medium grid size, the influence of two solvers, i.e. waveFoam and waveIsoFoam on the modelled overtopping volume was investigated. The turbulence model was not applied. Solver waveFoam is a segregated and iterative solver using a PISO algorithm, which is developed based on interFoam in the OpenFOAM framework. The traditional interFoam solver was based on the generalized Volume-of-Fluid (VOF) method to model multiphase wave flow. According to Larsen et al. (2018), the interface capture in interFoam is smeared over several cells depending on the grid size that is used. Since waveFoam was based on the interFoam solver, it also suffered from the shortcomings of diffusive interface capture method. This motivated the implementation of the isoAdvector scheme developed by Roenby et al. (2016). The isoAdvector scheme is a sharp interface capture technique. In waveIsoFoam, the new technique isoAdvector was coupled to capture the free water surface.

Figure 7 shows that the waveFoam solver leads to larger cumulative overtopping volume than the waveIsoFoam, which is in accordance with the results in Patil (2019). With isoAdector the exact position of the free surface was identified by an iso-line and was then advected in a geometric manner, making the surface sharper. Therefore, the water surface was captured better using waveIsoFoam, which is important for modelling the overtopping flow along the waterside slope and crest. However, the difference in the overtopping volume between these two solvers was not so significant as that in Patil (2019). This might be because the instantaneous overtopping flux in his study was quite small (less than 10^{-6} m^3/s) in comparison with the flux in our study (up to 1.7×10^{-3} m^3/s). The small overtopping flux was sensitive to the quality of free surface capture since the resulted overtopping flow layer is quite thin. The free surface could smear over three layers of grids using waveFoam, which further resulted in a clear overestimation of overtopping discharge. In contrast, the larger overtopping discharge in our study resulted in larger flow layer thickness. Thus, the overtopping discharge was less sensitive to the quality of free surface capture leading to less difference of overtopping volume between waveFoam and waveIsoFoam. The solver waveIsoFoam was adopted in the following calibration.

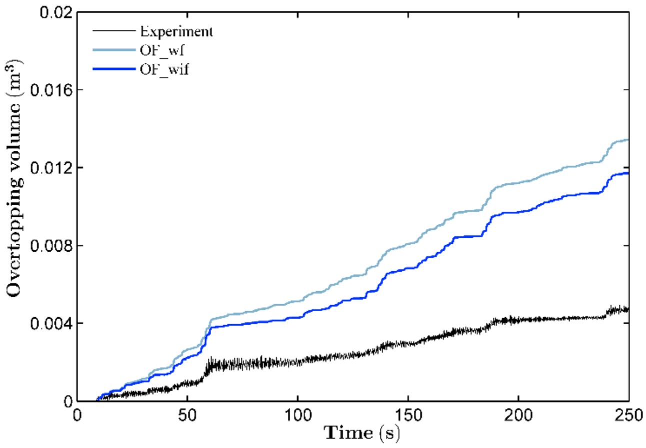

Figure 7. Time series of cumulative overtopping volume per meter width with different solvers (wf represents the solver waveFoam and wif represents the solver waveIsoFoam).

Turbulence model

Four simulations were done with the same medium grid size and the same solver waveIsoFoam, but with different turbulence models: 1) laminar flow, 2) the stabilized k-ω model with λ_1=0.875 and λ_2=0.05, 3) the stabilized k-ω model with λ_1=0.2 and λ_2=0.05 and 4) the stabilized k-ωSST model with λ_2=0.05. λ_1 is a stress limiter introduced by Wilcox (2006) for the k-ω turbulence model. This limiter essentially limits the eddy viscosity in regions where turbulence production exceeds the dissipation (Larsen and Fuhrman, 2018). Wilcox (2006) suggested $\lambda_1 = 0.875$. $\lambda_1 = 0.2$ is more in line with the Eq. (9) corresponding to $\lambda_1 = 0.26$ in Durbin (2009). λ_2 is another stress limiter added by Larsen and Fuhrman (2018) in the calculation of eddy viscosity to fix the problem that the turbulence levels are overestimated by conventional turbulence models. λ_2 defines the effective potential flow threshold and it will become actively only in a region of nearly potential flow. $\lambda_2 = 0.05$ as suggested by Larsen and Fuhrman (2018) was used in both k-ω model and k-ωSST model in this study.

Figure 8 shows that the modelled cumulative overtopping volume by applying a turbulence model was much less than that without a turbulence model. Waves break on the waterside slope surface and produce turbulence. The turbulence generated inside the water leads to wave energy dissipation, which results in less overtopping discharge. Therefore, turbulence model plays an important role in modelling wave overtopping when breaking occurs and should not be ignored in the numerical model. The performances of k-ω model with λ_1=0.875 and k-ωSST model were very similar, leading to almost the same cumulative overtopping volume. The k-ω model with λ_1=0.2 resulted in the overtopping volume which was closer to the measured overtopping volume. Therefore, k-ω model with λ_1=0.2 was adopted to account for the turbulence influence.

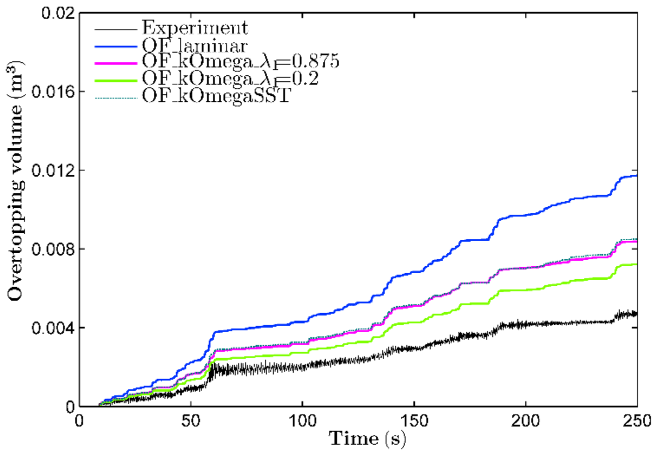

Figure 8. Time series of cumulative overtopping volume per meter width with different turbulence models.

Roughness height

The roughness of the waterside slope surface which was made of concrete was accounted for using a roughness constant C_s and the roughness height K_s included in the turbulence model. The roughness constant C_s accounts for the uniformity of the roughness elements on the surface and Nikuradse (1950) determined the value of C_s as 0.5 for the uniform and closely packed sand grains. In this study, the value of C_s was set at 0.5. The roughness height K_s represents the equivalent grain roughness (Nikuradse, 1950) and it was calibrated in this study for the concrete surface. It is worth mentioning that the roughness height K_s should be smaller than half the cell size (Van Bergeijk et al., 2020).

Three values of roughness height K_s (0.0001 m, 0.0005 m and 0.001 m) were tested. The roughness height applied in the simulations that are shown in Figure 8 is 0.0001 m. Figure 9 shows the results of cumulative volume using different roughness heights. These three simulations were performed with the same medium mesh, the same solver waveIsoFoam and the same turbulence model k-ω model ($\lambda_1 = 0.2$, λ_2=0.05). It can be observed from Figure 9 that as the roughness height increases the modelled overtopping volume decreases. K_s = 0.001 m leads to a good agreement between numerical and experimental time series of cumulative overtopping volume. Table 2 presents the model results of all simulations of 250 s for the model calibration.

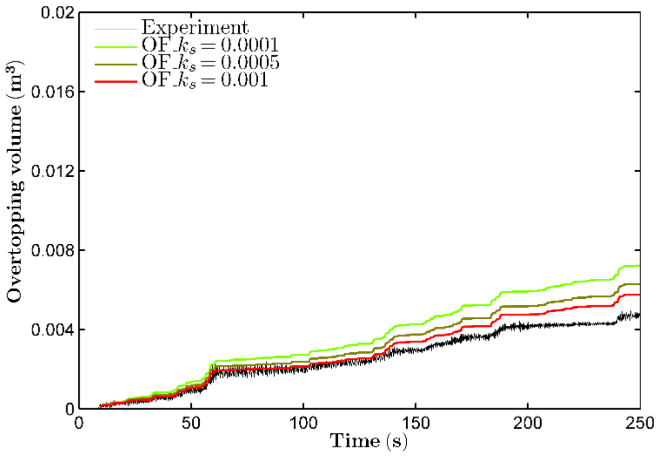

Figure 9. Time series of cumulative overtopping volume per meter width with different roughness heights.

Table 2. Modelled wave conditions and modelled average overtopping discharges (Experimental wave condition: Hm0 =0.123 m, Tm-1,0=1.72s and Experimental average overtopping discharge: q_ave = 0.92 l/s/m).

case name	mesh	solver	turbulence model	K_s [m]	H_{m0} [m]	$T_{m-1,0}$ [s]	q_ave [l/s/m]
OF_coarse	coarse	wf	laminar		0.123	1.74	3.0
OF_mediem(wf)	medium	wf	laminar		0.124	1.74	2.7
OF_fine	fine	wf	laminar		0.124	1.78	2.3
OF_wif	medium	wif	laminar		0.126	1.75	2.3
OF_kOmega_ λ1 = 0.875	medium	wif	kOmega(λ1=0.875)	0.0001	0.123	1.77	1.7
OF_kOmega_λ1 = 0.2	medium	wif	kOmega(λ1=0.2)	0.0001	0.123	1.78	1.4
OF_kOmegaSST	medium	wif	kOmegaSST	0.0001	0.123	1.78	1.7
OF_ks = 0.0005	medium	wif	kOmega(λ1=0.2)	0.0005	0.124	1.75	1.3
OF_ks = 0.001	medium	wif	kOmega(λ1=0.2)	0.001	0.123	1.78	1.1

MODEL VALIDATION

The calibrated model settings (medium mesh, waveIsoFoam, k-ω model with $\lambda_1 = 0.2$ and K_s=0.001 m) are validated using eight physical model tests (SS2-SS9) listed in Table 1 selected from Chen et al. (2020a). Each simulation ran for 500s which was sufficient for reliable estimates of average overtopping discharges in this study. Figure 10 shows the comparison between modelled and measured dimensionless average overtopping discharges. The red mark represents the case that was used for model calibration but for model calibration this case was simulated for 500 s instead of 250 s. The Nash-Sutcliffe model efficiency coefficient (NSE) was used to quantitatively estimate the performance of the numerical model. NSE = 1 represents a perfect agreement of numerical data to the experimental data. The NSE for the data shown in Figure 10 is 0.92, which demonstrates that the modelled results match very well with the measured results.

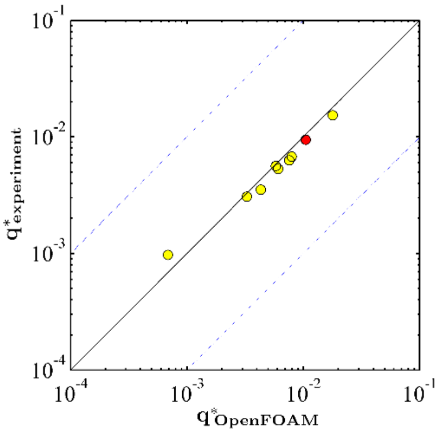

Figure 10. Comparison between modelled and measured dimensionless average overtopping discharges ($q^* = q_{ave}/\sqrt{(gH_{m0}^3)}$) in which the red mark corresponds to the case that is used for model calibration.

DISCUSSION

This paper presents a systematic calibration and validation of the OpenFOAM model for predicting the wave overtopping discharge subject to irregular waves at a dike that has a smooth straight waterside slope. Results of all simulations for calibrating the numerical model were plotted in Figure 11. Refining mesh can improve the performance of the OpenFOAM model for predicting the overtopping discharge at the expense of computational time. Applying the solver waveIsoFoam with medium mesh size can achieve an equivalent improvement of the model result to using waveFoam with refined mesh of 0.01 m × 0.01 m (0.005 m × 0.005 m for the mesh near the free surface). Therefore, it is recommended to apply waveIsoFoam to solve the numerical model for overtopping discharge using waves2Foam.

Including a turbulence model in the numerical model resulted in a significant decrease of the modelled overtopping volume compared to the modelled result without including a turbulence model. k-ω model with $\lambda_1 = 0.875$ and k-ωSST model yielded similar results of the overtopping volume. k-ω model with λ_1 =0.2 dealt with the turbulence influence caused by wave breaking on the overtopping discharge better in this study, leading to the modelled overtopping volume coming closer to the measured result. With the turbulence model, the numerical model still overestimated the overtopping volume. Thus, the roughness height K_s was increased from 0.0001 m to 0.001 m to represent the roughness of the smooth surface. It is not recommended to further increase this value too much as the grid size should be larger than twice the roughness height and increasing roughness height would lead to coarse mesh near the surface which can reduce the model accuracy of predicting the overtopping discharge. Besides, too large roughness height will violate its physical meaning for smooth surface.

There is a good agreement between the experimental and numerical results using the roughness height K_s = 0.001 m as shown in Figure 11 despite of a slight overestimation of the overtopping volume predicted by the numerical model. This overestimation might be explained as follows. The modelled incident waves were not exactly the same as the incident waves in the experiments and minor differences in the free surface in front of the dike could result in differences in the amount of overtopped water. It is also worth noting that the numerical model can well capture the individual overtopping volumes.

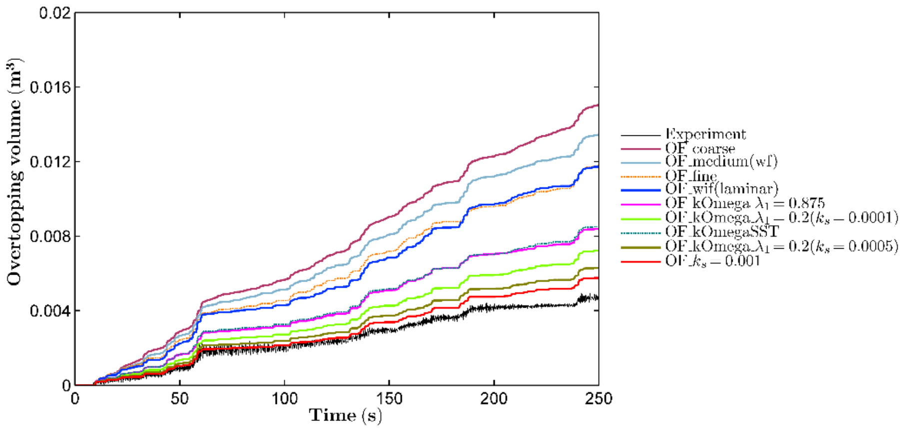

Figure 11. Time series of cumulative overtopping volume per meter width of all simulations for model calibration.

CONCLUSIONS

In this study, the performance of the OpenFOAM model for simulating the wave overtopping discharge at a dike with a smooth straight was systematically calibrated and validated. We investigated the influence of grid size, solver, turbulence model and roughness height on the modelled overtopping volumes over a dike. It has been shown that finer grid size could improve the performance of the numerical model. The medium grid size of 0.02 m × 0.02 m (0.01 m × 0.01 m for the mesh near the free surface) was adopted in this study to achieve a balance between the model accuracy and the computational time. The solver waveIsoFoam showed better performance than the solver waveFoam with respect to the wave overtopping discharge. The calibration results show that the application of turbulence model significantly affected the modelled results of the cumulative overtopping volume and therefore the turbulence model should be included to account for the turbulence influence when wave breaking is present. The k-ω model with λ_1=0.2 and λ_2=0.05 was adopted in this study considering this turbulence model lead to better result of the overtopping volume. The roughness height K_s was calibrated as 0.001 m for the smooth surface which was made of concrete. Above all, the calibrated optimal model setting for modelling the wave overtopping discharge at an impermeable dike in this study are: medium grid size of 0.02 m × 0.02 m (0.01 m × 0.01 m for the mesh near the free surface), the solver waveIsoFoam, k-ω model (λ_1=0.2, λ_2=0.05) and roughness height K_s = 0.001 m.

The calibrated model settings were validated using eight tests from Chen et al. (2020a). The results show that the numerical model with the calibrated settings is capable of accurately predicting the average overtopping discharge at an impermeable dike with a smooth straight slope with NSE = 0.92. It is foreseen that the present systematic calibration and validation of the OpenFOAM model can provide some reference for users to simulate the overtopping discharge at an impermeable dike more properly.

ACKNOWLEDGMENTS

The first author thanks the China Scholarship Council (CSC) for providing the research grant. This work is also part of the All-Risk research programme, with project number P15-21, which is partly financed by the Netherlands Organisation for Scientific Research (NWO).

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