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Numerical Modelling of Overtopping Flow Velocity and Layer Thickness at the Waterside Edge of the Dike Crest

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Abstract

The overtopping flow velocity and layer thickness are closely related to the stability of coastal structures. Some empirical formulas are available for estimating the overtopping flow velocities and layer thicknesses. However, these empirical equations were derived based on experiments where only limited amount of wave conditions and dike configurations (mostly smooth straight waterside slopes) were tested. Therefore, the extrapolation of existing empirical equations to cases that are outside of the applicable ranges remains uncertain. Numerical modelling has become an important complementary tool to physical experiments. In this study, we developed a 2DV numerical model based on the OpenFOAM framework to simulate the overtopping flow velocity and layer thickness at the waterside edge of the dike crest. This model is validated by comparing the modelled overtopping flow parameters with the measured ones from physical experiments. The model validation shows that the 2DV OpenFOAM model is capable of predicting the overtopping flow parameters with a low probability (2%) of exceedance reasonably well although the overtopping layer thickness is slightly overestimated.

Keywords: OpenFOAM; Overtopping flow parameters; Numerical model; CFD

1. INTRODUCTION

The average overtopping discharge is often used as design parameter for dikes. However, the average overtopping discharge does not describe the extreme individual overtopping events. During extreme events like a storm, dike failures are often initiated by the overtopping flow velocity and layer thickness related to individual overtopping events (Schüttrumpf, 2001; Bomers et al., 2018). The flow parameters, including flow velocity and layer thickness, are closely related to the stability of coastal structures (Argente et al., 2018; Mares-Nasarre et al., 2021). The overtopping flow velocity and layer thickness are used as input in some erosion models (Dean et al., 2010; Hoffmans, 2012; Van Bergeijk et al., 2021) to estimate the cover erosion and stability of earthen dikes. Pedestrian safety during wave overtopping was also assessed using the flow velocity and layer thickness (Bae et al., 2016; Suzuki et al., 2020). Therefore, flow parameters including the flow velocity and layer thickness are also important for the design and reliability assessment of coastal structures.

The flow velocity and layer thickness with a low probability of exceedance (2%) during a storm event are usually used to describe the overtopping flow since these extreme values are more relevant for predictions of the cover erosion or dike failures on the landward slopes. Several formulas are available for predicting the extreme flow velocity and layer thickness at the waterside slope, the crest and the landward slope. The flow characteristics at the waterside edge of the dike crest are especially important since they provide boundary conditions for estimates of flow characteristics along the crest and the landward slope. The first formulas for estimating the overtopping flow velocity and layer thickness were proposed by Schüttrumpf (2001) based on the physical model tests and theoretical analysis. According to the formulas, the calculation of the flow velocity and layer thickness at the waterside edge of the dike crest depends on the wave run-up height ($R_{u2\%}$) and the crest freeboard (R_c). Van Gent (2002a,b) developed formulas that have similar form with those by Schüttrumpf (2001) but have different values of the empirical coefficients. The results were later combined in Schüttrumpf and Van Gent (2003). EurOtop (2018) also provided formulas for estimating the flow velocity and layer thickness at the waterside of the dike crest which are similar with those proposed by Schüttrumpf and Van Gent (2003). Formentin et al. (2019) performed numerical computations based on which they refitted the formulas by Schüttrumpf and Van Gent (2003) and proposed new forms of formulas of flow parameters.

The existing formulas from previous research are compared in Figure 1. This Figure 1 shows that there are only minor differences in flow velocity among the different empirical formulas except for the Formentin et al. (2019) equation. The equation proposed by Formentin et al. (2019) was calibrated against the values of $u_{2\%}$ obtained based on the average values of the velocities along the vertical above the dike crest while the other empirical equations were derived based on the measurements of velocity from micro-propellers installed at a fixed height above the crest. This could be one cause for the significant difference between Formentin et al. (2019) formula and other formulas. It is worth noting in Figure 1b that the layer thickness calculated using Schüttrumpf (2001) formula is almost twice that given by the Van Gent (2002a) formula. The differences can be explained by different dike geometries and instruments (Schüttrumpf and Van Gent, 2003). Additionally, the 2% values of velocity and layer thickness in Schüttrumpf (2001) were obtained based on only about 50 waves while $u_{2\%}$ and $h_{2\%}$ in Van Gent (2002a,b) were calculated based on 1000 waves, which could also partly explain the differences. The Formentin et al. (2019) formula overall overestimates the layer thickness compared to other formulas, which could be caused by the overestimation of layer thicknesses produced by the numerical model based on which the formula was derived. For $R_{u2\%} - R_c < 0.2$ m, which is the common case in small-scale physical tests, the results given by Van Gent (2002a,b), EurOtop (2018) and Formentin et al. (2019) are very close. Even though there is extensive literature on the overtopping flow characteristics at dikes, previous research mainly considered the dike configurations with smooth straight waterside slopes. It still remains unclear if these formulas are valid for slopes with other configurations like slopes that have a berm.

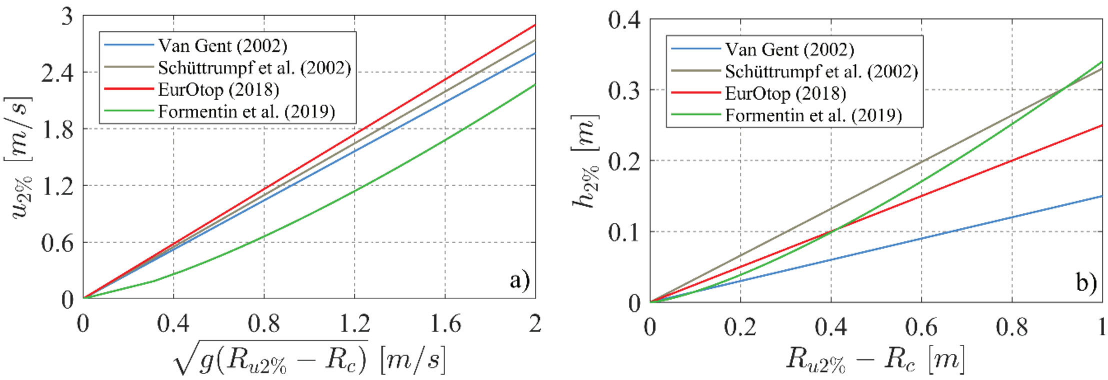


Figure 1. Comparison of existing empirical equations for a) overtopping flow velocity and b) layer thickness at smooth slopes; A slope of 1/4 was applied for calculations using EurOtop (2018) equations and Formentin et al. (2019) equations.

In order to take a wider range of dike configurations into account, a 2DV numerical model was developed in this study. The OpenFOAM model was used to set up the numerical model considering OpenFOAM is an open-source computational fluid dynamic framework which has been applied in many fields of aero- and hydrodynamics. The objective of this study is to explore the capability of OpenFOAM in simulating the overtopping flow velocity and layer thickness at dikes. In this study, we only focused on the waterside edge of the dike crest since the flow parameters at this location provide boundary conditions for estimating the flow parameters along the crest and landward slope.

2. NUMERICAL METHOD

2.1 Description of Experiments

Physical model tests performed by Van Gent (2002a,b) were used to validate the OpenFOAM model. The detailed introduction about the physical experiments can be found in Van Gent (2002b). A brief description is also given here. The small-scale physical model tests were conducted in the Scheldt Flume at Deltares in the Netherlands. This flume is 55 m long and 1.2 m high. A foreshore with a slope of 1:100 over a length of about 30 m was applied in front of the dike as shown in Figure 2. A step with a 1:10 slope was constructed between the wave board and the start of the foreshore to obtain a sufficient depth at the wave board. The distance between the toe of the structure and the wave board was 40 m. The slopes of the dike were smooth. The crest elevation was 0.6 m above the bottom at the toe. Three wave gauges were installed near the toe to measure the surface elevation. The incident waves at the toe were determined using the method by Mansard and Funke (1980). The flow velocity and layer thickness at the waterside edge of the crest were measured.

Ten tests were selected from the experiments to validate the 2DV OpenFOAM model as listed in Tables 1 and 2. The irregulars waves applied in tests T101-T104 were generated based on the TMA-spectra (Bouws et al., 1985). Irregular waves in tests T201-T206 were generated based on the double-peaked wave energy spectra which were created by superposition of two single-peaked TMA-spectra. The distance between the two individual peaks (T_{p2}/T_{p1}) was varied in the range of 0.4 to 1.0. The ratio between the energy in each individual TMA spectrum was 1.0. The applied wave spectra are present in Figure 3.

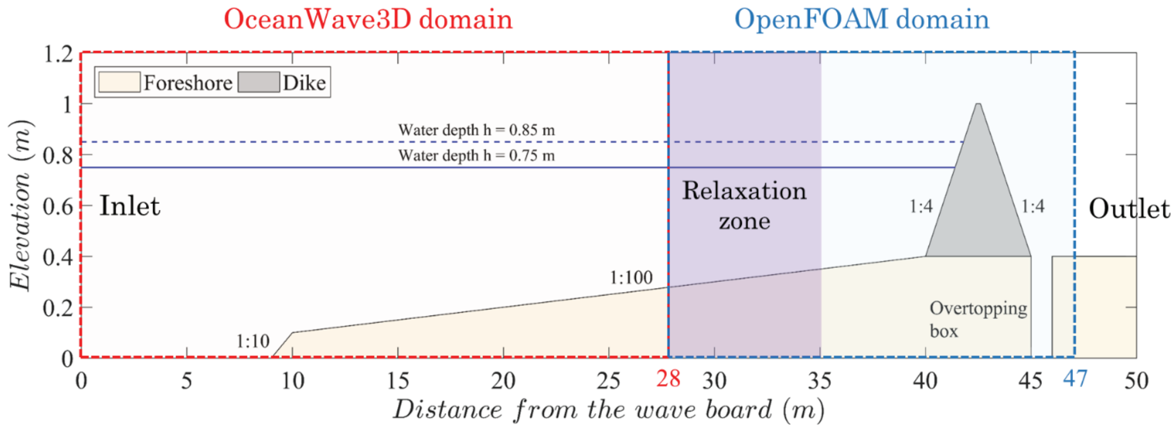
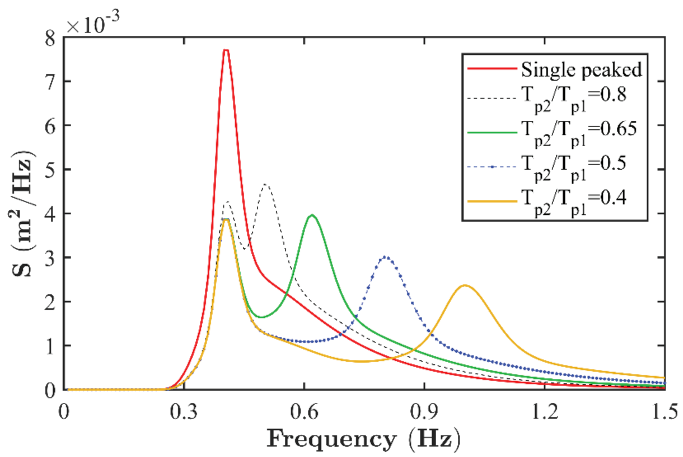
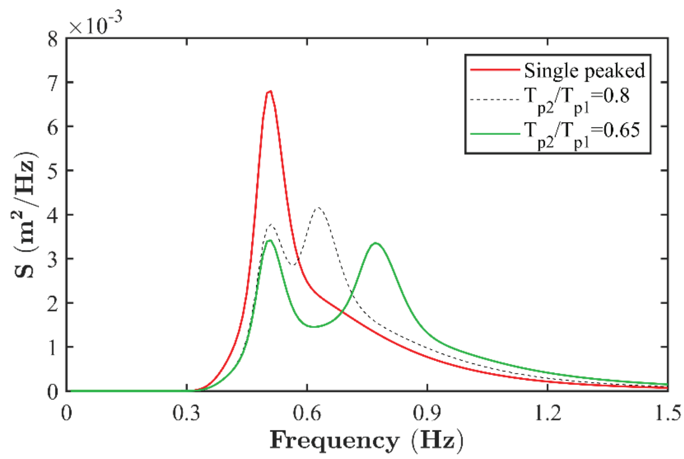


Figure 2. Set-up of the physical model in Van Gent (2002b) and numerical domain.



(a) Wave energy spectra with the lowest peak frequency at $T_{p1} = 2.5$ s.



(b) Wave energy spectra with the lowest peak frequency at $T_{p1} = 2.0$ s.

Figure 3. Single and double-peaked wave energy spectra based on which the irregular waves were generated according to Van Gent (2002b).

Table 1. Ten tests with input parameters for the wave generator selected from Van Gent (2002b).

Test	h_toe	H_{m0} [m]	T_{p1} [s]	T_{p2}/T_{p1}
T101	0.35	0.15	2.5	1
T102	0.35	0.15	2.0	1
T103	0.4	0.15	2.5	1
T104	0.45	0.15	2.0	1
T201	0.4	0.15	2.5	0.8
T202	0.4	0.15	2.5	0.65
T203	0.4	0.15	2.5	0.5
T204	0.4	0.15	2.5	0.4
T205	0.4	0.15	2.0	0.8
T206	0.4	0.15	2.0	0.65

Table 2. Measured wave conditions and measured flow parameters at the waterside edge of the dike crest from Van Gent (2002b).

Test	h_toe	H_{m0} [m]	$T_{m-1,0}$ [s]	$h_{2\%}$ [m]	$u_{2\%}$ [m/s]
T101	0.35	0.149	2.16	0.0143	1.53
T102	0.35	0.142	1.84	0.0058	0.99
T103	0.4	0.153	2.14	0.0212	1.74
T104	0.45	0.147	1.78	0.0204	1.64
T201	0.4	0.152	2.03	0.016	1.55
T202	0.4	0.148	1.92	0.014	1.53
T203	0.4	0.139	1.84	0.0117	1.44
T204	0.4	0.13	1.86	0.0101	1.29
T205	0.4	0.142	1.69	0.0076	1.09
T206	0.4	0.138	1.62	0.0076	1.08

2.2 Model Set-up

The 2DV OpenFOAM model developed by Chen et al. (2021), which has been validated for simulating the average overtopping discharge, was applied in this study with the layout of the model adapted according to the physical tests in Van Gent (2002b). Simulating the entire physical domain in an OpenFOAM model would be computationally expensive. Therefore, the OceanWave3D, which is a computationally cheaper solver, simulated the wave propagation between 0 m and 28 m from the wave board. The rest of the domain was simulated in the OpenFOAM model as illustrated in Figure 2. The irregular waves were generated and absorbed by using the waves2Foam toolbox developed by Jacobsen et al. (2012). Steering files of wave board motion created based on the single-peaked or double-peaked TMA spectra were first input to the OceanWave3D model. The generated waves in OceanWave3D provided input for the waves2Foam model (for detailed information about the coupling method, reference is made to Paulsen et al., 2014). It is worth mentioning that the steering files were not the original files of the experiments. Thus, the generated time series of free surface elevation were not the same as the experimental ones but the input wave properties including spectral significant wave height and spectral wave period were consistent with those in the physical model tests.

The mesh was generated using *BlockMesh*. The background mesh from the inlet boundary to the start of the dike was orthogonal and conformal with grid size of 0.026 m × 0.026 m. In order to accurately model the wave propagation, the grids near the free water surface were refined to 0.013 m × 0.013 m. Quadrilateral grids parallel with the slope surface were created in the area where the structure located. Ten layers of grid cells with the grid size of 0.005 m in vertical direction were applied near the structure surface to resolve the overtopping flow. The turbulence was accounted for by applying a stabilized $k - \omega$ turbulence model developed by Larsen and Fuhrman (2018).

Each test was simulated for about 600 s, resulting in 280~350 waves depending on the wave period. The flow velocity and water layer thickness were obtained using 30 probes defined uniformly between 1.0 m and 1.05 m in vertical direction at the waterside edge of the crest in the OpenFOAM® model. The Nash-Sutcliff model efficiency coefficient (NSE) (Nash and Sutcliffe, 1970) is used to assess the predictive power of the OpenFOAM model.

3. RESULTS

3.1 Wave Properties

Since the overtopping flow parameters are closely related to the incident wave properties, the numerically modelled significant wave height and spectral wave period were first compared with the experimentally measured results as shown in Figure 4. This Figure 4 shows that there is a good agreement between the numerically and experimentally measured significant wave height while the spectral wave period was obviously overestimated by the numerical model compared to the experimental results. Extending the relaxation zone at the inlet boundary and refining the mesh did not lead to better results of the modeled wave period. The overestimation of the wave period could be related to wave breaking. The wave breaking could happen due to the relatively shallow water and it might not be addressed very well by the OceanWave3D, which could further lead to inaccuracies in the wave period. It is expected that the overestimation of the wave period will cause overestimation of overtopping flow velocities and layer thicknesses.

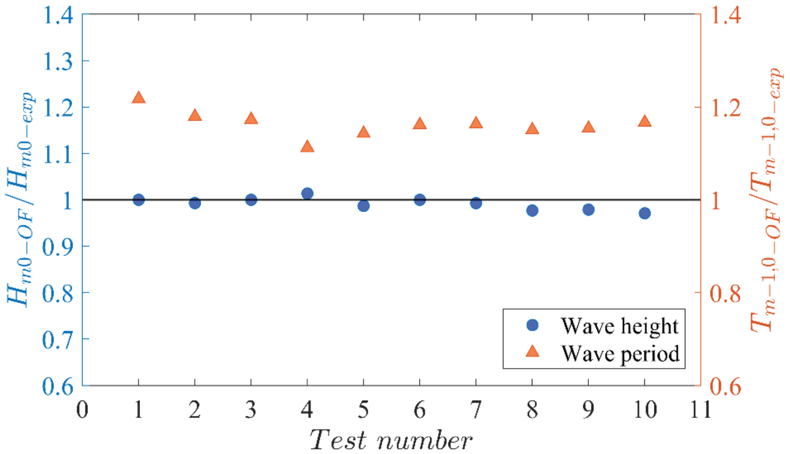


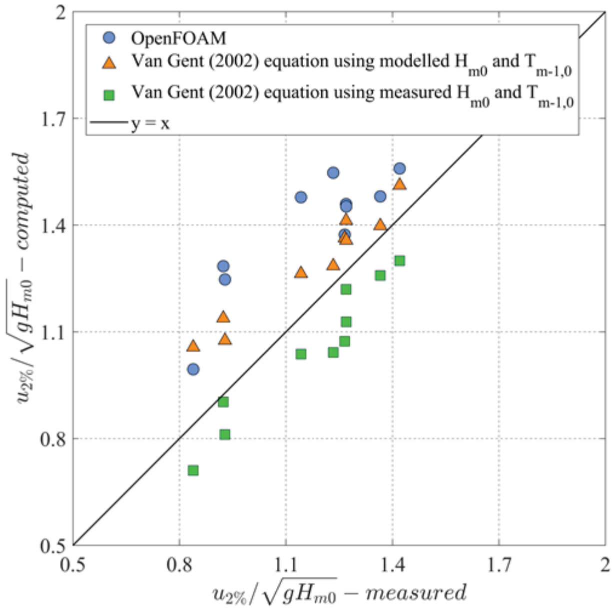
Figure 4. Comparison between modelled and measured wave characteristics significant (wave height H_{m0} and spectral wave period $T_{m-1,0}$).

3.2 Flow Velocity and Layer Thickness

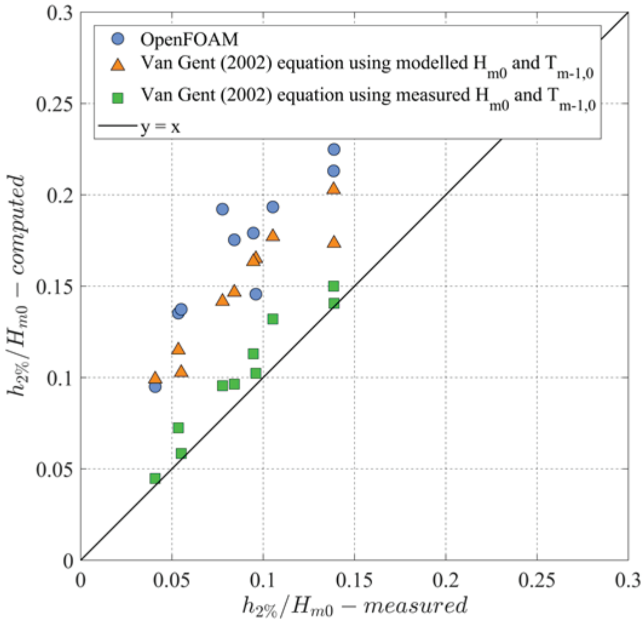
The modelled flow parameters were compared both to the measured results and to the empirical equations derived by Van Gent (2002a,b) (see Figure 5). The flow velocities were overestimated by the numerical model compared with the measured values. However, it is worth noting that the modelled flow velocities match well with the calculating values using the modelled wave characteristics (H_{m0} and $T_{m-1,0}$) by empirical equations. Additionally, there is a relatively good agreement between the calculated flow velocities using the measured wave characteristics and the measured velocities, which makes sense because the empirical equations were derived based on these experiments. The numerical model also over-predicted the layer thickness while the modelled results match reasonably well with the empirical equations using the modelled wave characteristics. Overall, there is a reasonably good agreement between the modelled parameters and the calculated ones using the modelled H_{m0} and $T_{m-1,0}$ by the empirical equations. This indicates that the overestimation of flow parameters given by the numerical model was mainly caused by the overestimation of the wave period considering the wave height was modelled accurately. To make the numerical and experimental results comparable, the numerical flow parameters were modified based on the calculated results using the Van Gent (2002a,b) empirical equations:

$$X_{2\%OFmod} = X_{2\%OF}/(X_{2\%cal-OF}/X_{2\%cal-exp}) \qquad [1]$$

In which $X_{2\%OFmod}$ represents the modified numerical flow velocity or layer thickness; $X_{2\%OF}$ denotes the original numerical flow parameters; $X_{2\%cal-OF}$ is the calculated flow parameters using the Van Gent (2002a,b) equations in which the numerical wave properties are used and $X_{2\%cal-exp}$ represents the calculated flow parameters using the measured wave properties.



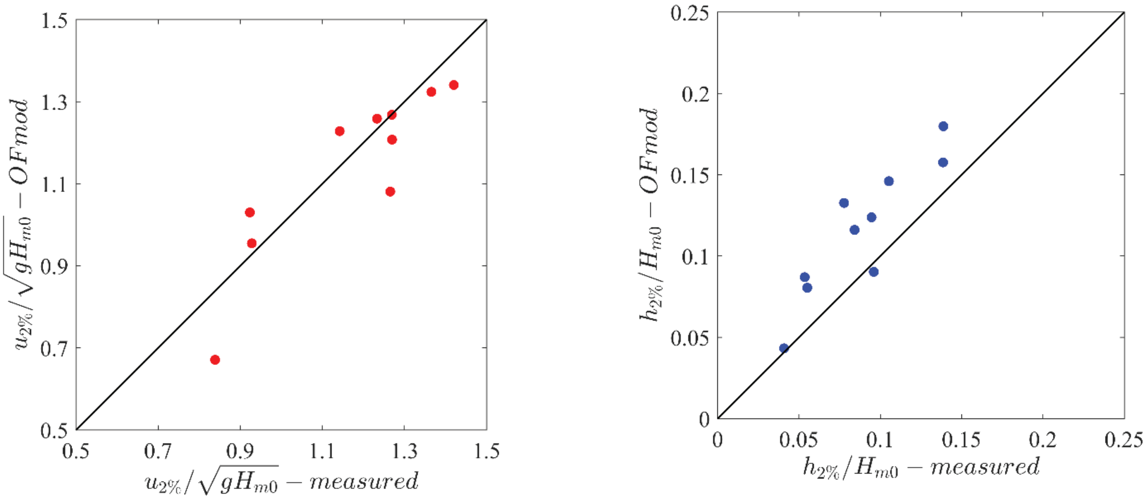
(a) Flow velocity



(b) Layer thickness

Figure 5. Comparison between measured and estimated flow parameters exceeded by 2% of the incident waves given by the OpenFOAM model and empirical equations.

Figure 6 shows the comparisons between the modified numerical flow parameters and the experimentally measured results. The NSE for the comparison of the flow velocity is 0.75, indicating a good agreement while the NSE for the layer thickness is only 0.03. The main cause for the low value of NSE is the overestimation of the layer thickness produced by the OpenFOAM model with a factor of 1.3. Dividing the modified modelled results by 1.3 increases the NSE from 0.03 to 0.83.



(a) Flow velocity (b) Layer thickness

Figure 6. Comparison between the measured flow parameters and the modified flow parameters given by the OpenFOAM model taking the overestimation of wave period into account.

4. DISCUSSION

4.1 Performance of the numerical model

The performance of the OpenFOAM model on simulating the overtopping flow velocities and layer thicknesses was validated in this study by comparing the modelled results to the measured flow parameters. The spectral wave period was overestimated by the numerical model, which might be caused by the Insufficient capability of the OceanWave3D in modelling the wave breaking. The numerical model is capable of predicting the flow velocity with a good accuracy. However, it gives an overestimation of the layer thickness with a factor of 1.3. This overestimation can be related to the quality of free surface capture. The interface between water and air could smear out over two or three layers of grids in the numerical model, which can further result in an overestimation of the layer thickness. Refining the mesh near the waterside slope and crest can to some extent reduce the overestimation. However, a fine mesh would significantly increase the computational time. Therefore, the grid size of 0.005 m vertical direction is adopted to comprise between the computational efficiency and the model accuracy of layer thicknesses. The overestimation of the layer thickness with a factor of 1.3 is regarded as being acceptable considering the spreading that is normally present when dealing with measurements of wave overtopping flow parameters (e.g. Figure 9 in Mares-Nasarre et al., 2019).

4.1 Limitations and applicability

In this present study, it takes about one week to compute one simulation for about 300 waves using 3 processors (3.6GHz) in parallel. The computational cost of the 2D simulations is acceptable considering the good model accuracy on predicting the average overtopping discharge and overtopping flow characteristics. Nevertheless, the computational efficiency of the 2D model still requires improvement to be competitive with NSWE models in terms of computation.

The 2D numerical model set up in this study has the potential to serve as a complementary tool for empirical methods to predict the overtopping flow parameters. It is flexible to change the dike configurations and wave conditions in the numerical model. For example, the berm and/or roughness can be implemented in the OpenFOAM model. The flow parameters are closely related to dike cover erosion. Earthen dikes covered by grass are vulnerable to overtopping (Van Bergeijk et al., 2020). The high flow velocities during the wave run-up at the waterside slope, overtopping at the crest and landward slope can result in grass cover erosion. Several erosion models (e.g. Van der Meer et al., 2010; Hoffmans,2012) are available to estimate the cover erosion which require the hydraulic load as input. The modelled flow characteristics can be used as input to estimate the cumulative erosion damage or depth on the crest and the landward slope of a storm event using the cumulative overload method proposed by Van der Meer et al. (2010) or analytical grass-erosion model as described in Van Bergeijk et al. (2021). Furthermore, it is easy to extract the hydraulic load such as flow velocity, shear stress and pressure at any location along the waterside slope and crest from the numerical model. The flow characteristics are also key parameters to assess the pedestrian safety when standing on the coastal structures during the overtopping events (Mares-Nasarre et al., 2019). Suzuki et al. (2020) suggested that the overtopping risk was better characterised by time dependent flow velocity and layer thickness than maximum flow parameters. Our numerical model can provide time series of flow parameters. Sandoval and Bruce (2018) provided different criterion for human stability on coastal structures. For example, the criteria for a tall adult can be expressed as a stability line by the combination of U and h. By comparing the modelled flow velocities and layer thicknesses to the stability line, it is possible to estimate the stability of an adult on the crest of coastal structures under different wave conditions. This could provide some insight into the necessity of reinforcement of dikes for the accessibility criteria.

5. CONCLUSIONS

In this study, we validated the 2DV OpenFOAM model for simulating the overtopping flow velocity and layer thickness at the waterside edge of the dike crest by comparing to the experiments presented in Van Gent (2002a,b). The numerical model is capable of reproducing the wave height well while it gives an overestimation of the wave period. This overestimation could be more related to the OceanWave3D and therefore it is recommended to improve the capability of OceanWave3D in addressing the wave breaking. The flow velocity can be simulated reasonably well by the 2D OpenFOAM model after performing a modification by taking the overestimation of the wave period into account. The flow layer thicknesses are still overestimated with a factor of 1.3. It is recommended to improve the accuracy of the numerical model in predicting the layer thicknesses in the future. Nevertheless, the numerical model has a large number of potential applications, for instance, providing insight into dependencies of parameters.

6. ACKNOWLEDGEMENTS

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