A Numerical Simulator for Wave Overtopping

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Abstract: *Wave overtopping and the propagation of the waves on the crest and the landward side of a coastal dike is investigated numerically in this study. Wave overtopping conditions are simulated using the concept of the Wave Overtopping Simulator (WOS). The computed results are compared against proposed empirical relationships based on available field measurements.*
The RANS equations, a turbulence model of the k-ε type and the VOF method are solved numerically, using the CFD code FLUENT, for "tracking" the free surface and the head of the "current" from the dike crest to the toe of the landward dike slope. The latter as well as the crest are usually covered by grass and its effect on the wave propagation over the crest and the landward slope is investigated.

Keywords: *Wave overtopping, Simulator, Coastal dikes, Dike crest, Landward slope, Grass cover*

1. INTRODUCTION

The safety of a large part of inhabited areas of the Netherlands depends on sea dikes. Due to climate change, a sea level rise is predicted and in addition to stronger storms and more wave attack, wave overtopping on the current dikes will increase. For that reason it is essential to evaluate the tolerance of the existing dikes and also to propose construction methods in order to increase the strength of dikes for cases which is necessary.

Wave overtopping occurs when the water level in front of the dike and the waves are high enough that after breaking on the outer slope, the wave run up exceeds the crest level. Wave overtopping is quantified as the mean discharge per meter of width, q (l/s m^{-1} or m^3/s m^{-1}) that is reaching the inner slope of the dike. It has a negative effect on the stability of the grass cover layer on the inner slope of the dike and can result in severe damage.

In order to create full scale overtopping conditions on a real inner slope of a dike the Wave Overtopping Simulator has been developed. The Wave Overtopping Simulator is a container which is filled continuously with a pump discharge and is opened with a pneumatic valve after fixed time periods. The water flows out, resembling an overtopping wave. The design and the calibration of the Wave Overtopping Simulator have been described by Van der Meer (2007) and also Van der Meer et al (2006, 2007 and 2008).

In the past years a significant amount of field experiments related to the impact of wave overtopping on the sea dikes have been performed using the Wave Overtopping Simulator and results have been described by Akkerman et al (2007a and 2007b) and Steendam et al (2008). Experimental results, using the Wave Overtopping Simulator, as well as equations for flow depth and flow velocity under wave overtopping have been also presented by Van der Meer et al (2010).

In the present work the effect of wave overtopping on the crest and the inner slope of a sea dike is studied numerically. The wave overtopping conditions are created by simulating the Wave Overtopping Simulator (WOS) and the computed results are tested against available field experiments and empirical relationships for the prediction of maximum flow depth and velocity at various locations at the dike crest and the landward slope (Van der Meer, 2010). A comparison between smooth and vegetated (rough) dike is presented for studying the vegetation effects on wave overtopping.

2. DIKE GEOMETRY-CASES STUDIED

The dike geometry has been presented by Van der Meer et al. (2010). The length of the dike crest is 2 m at a height of 2.7 m above the ground. The landward slope is equal to 1:3.7 at the upper part, while at the lower part is equal to 1:5.2. Five measurement locations have been selected as it is shown in figure 1. The first location is at the end of the crest (Board-1), while the next four locations are along the landward slope (Board-2 to 5). Specifically Boards-2 and 3 are at the upper part (slope 1:3.7), while Boards-4 and 5 are in the region where the slope is equal to 1:5.2.

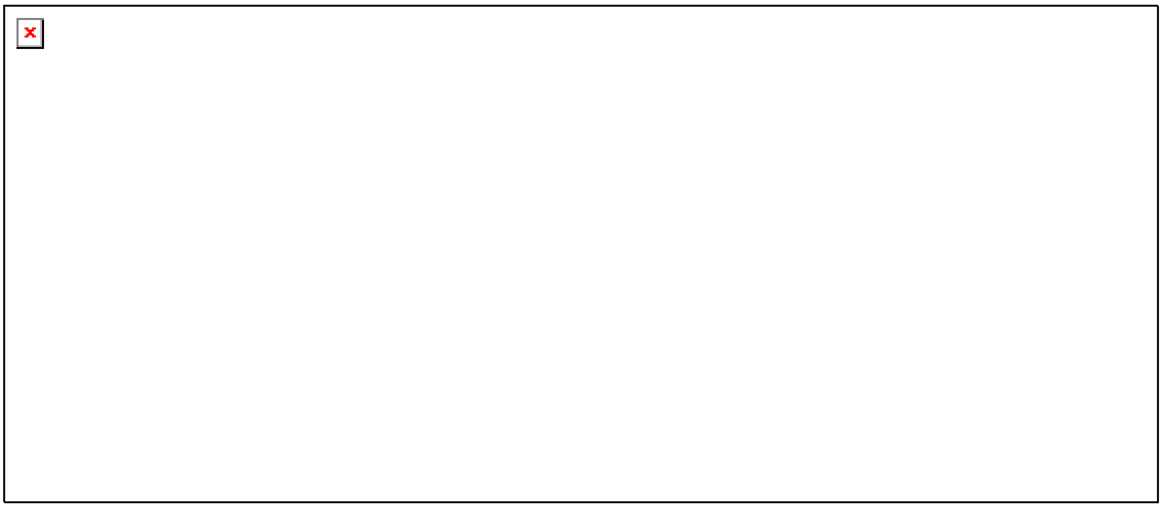

Figure 1: Wave Overtopping Simulator, Dike Geometry and Measuring Boards

In the present study cases with 3 different overtopping volumes, equal to 600, 1000 and 2000 l/m have been simulated. For these overtopping volumes cases with smooth and also vegetated dike crest and landward slope have been examined. The presence of vegetation has been simulated as roughness with a height equal to 4 cm.

2.1. Numerical procedure

The FLUENT CFD code, (FLUENT Inc., 2001) is applied which uses a control-volume technique to convert the governing equations to algebraic equations which can be solved numerically. For the construction of the grids the GAMBIT program was used. The grids were two-dimensional, structured and the shape of the cells was orthogonal. The number of computational cells for the cases which are studied is equal to 200000. The FLUENT code solves the Reynolds-Averaged Navier-Stokes (RANS) equations in conjuction with the transport equations of turbulent kinetic energy and dissipation rate which are applied from the use of the k-ε type turbulence model. The VOF method is also enabled for “tracking” the free surface from the dike crest to the toe of the landward dike slope. The simulations are time-dependent and the time step which is used is equal to $5x10^{-4}$ s.

Initially, water is present in the tank while air is in the rest of the computational domain (Figure 2). The water flows through the exit of the tank due to gravity, while the initial values of turbulent kinetic energy and dissipation rate are equal to 10^{-4} and 10^{-5} respectively. The RANS equations and the transport equations of turbulent kinetic energy and dissipation rate are non-linear and coupled which means that during a time step several iterations of the solution loop are performed before a converged solution is obtained. With regard to the VOF method the code solves the volume fraction equation once for each time step which means that the other convective flux coefficients are not updated after each iteration during the time step.

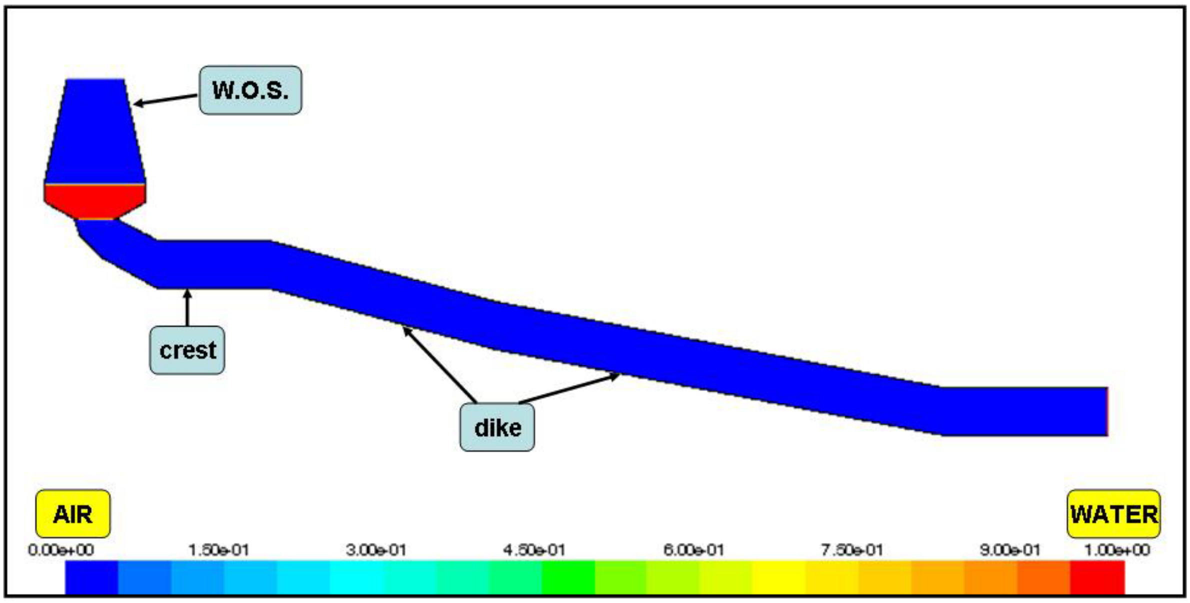

Figure 2: Computational Domain and Volume of fraction (water) at t=0.0 s

3. ANALYSIS OF RESULTS

In figure 3 the variation of the flow depth with time is shown for the three water volumes of the simulator and smooth and rough cover. For all cases the flow depth increases suddenly in the beginning as the wave passes from a particular location. The maximum flow depth increases with increasing water volume release and decreases as the wave travels along the landward slope of the dike. The effect of surface roughness (vegetation) is to increase the flow depth at all locations, due to increased drag resistance and the same amount of water release. The variation of the flow depth with time is also shown in figure 4 at three locations (Board 1, 3 and 5) for the three overtopping volumes and for the rough dike. In the same figure the variation of the flow velocity with time is shown and hence the changes of the main flow characteristics as the wave travels along the crest and the landward side of the dike are clearly shown.

The variation of the flow velocity with time is shown in figure 5 for the same conditions and at the same locations. Again the flow velocity increases suddenly in the beginning, however the time at which the velocity is maximum does not coincide with that of the maximum flow depth. The maximum velocity at the initial part of the landward slope is approximately equal with that at the crest and increases at the end of the slope (Board 5). At the landward slope of the dike the duration of high velocities is greater than that at the dike crest due to the increased bed slope. The effect of roughness on the maximum flow velocity is significant at the end of the landward step since the wave energy has been reduced significantly due to the resistance of the rough surface. Flow velocities for a smooth dike differ than those for a rough dike at the end of the wave passing from a particular location.

In figure 6 the variation of the computed maximum flow depth and velocity with the overtopping wave volume is shown together with an empirical relationship, based on field measurements with the wave overtopping simulator, proposed by Van der Meer et al (2010). The agreement between the computed maximum flow depth and that predicted by the expression $h=0.133V^{0.5}$ (h=flow depth (m) and V=volume (m^3/m)) is satisfactory for the Board 1 (dike crest) while the flow depth at other Boards in the landward slope of the dike are lower. Similar behaviour is indicated by the measured flow depths of Van der Meer et al (2010). The computed maximum velocities are shown to be increased with regard to those of the proposed relationship $u=0.5V^{0.34}$ (u=flow velocity (m/s)), however the difficulty in measuring the maximum velocity in the field as well as the omission of the air entrainment in the computations may contribute to such discrepancies.

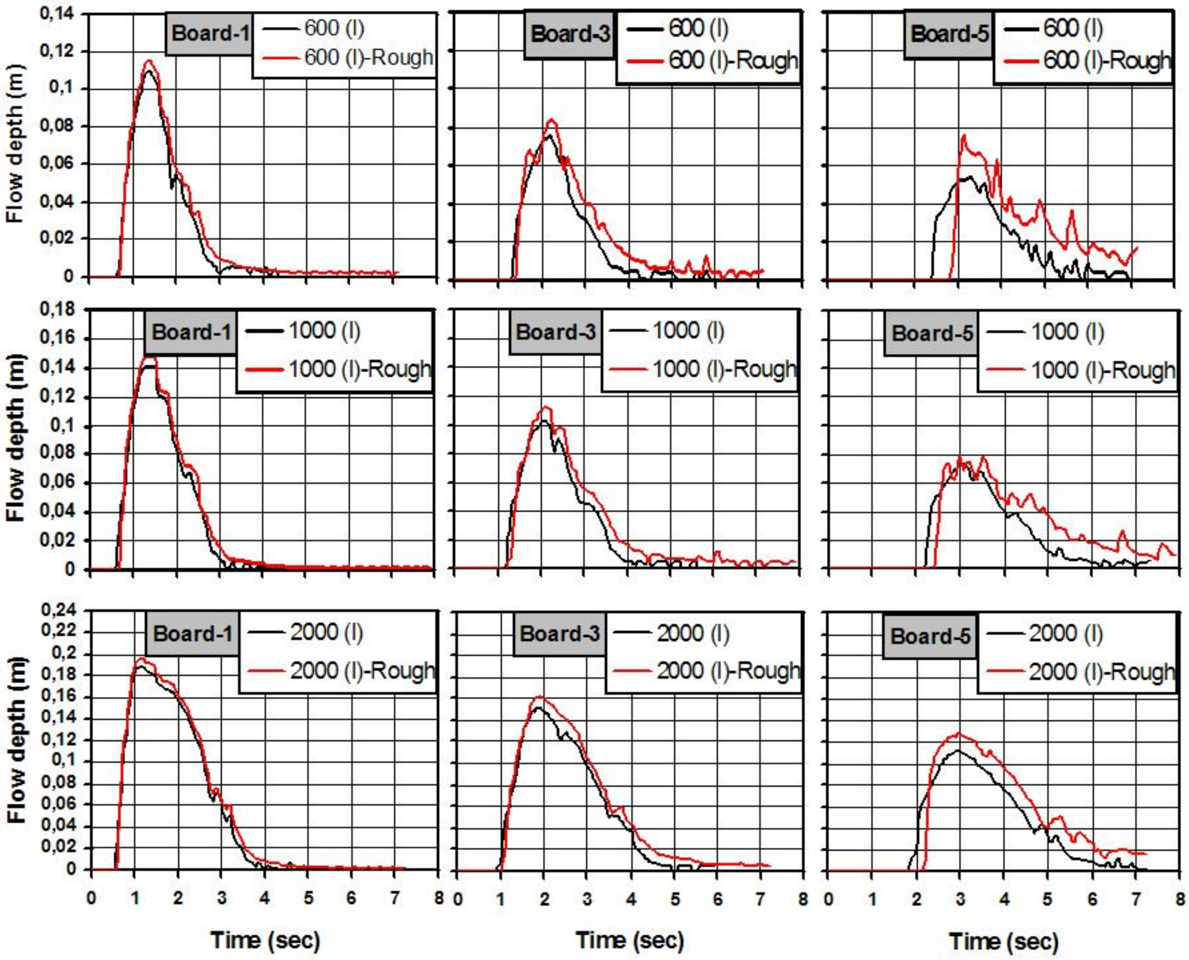

Figure 3: Variation of flow depth with time various locations

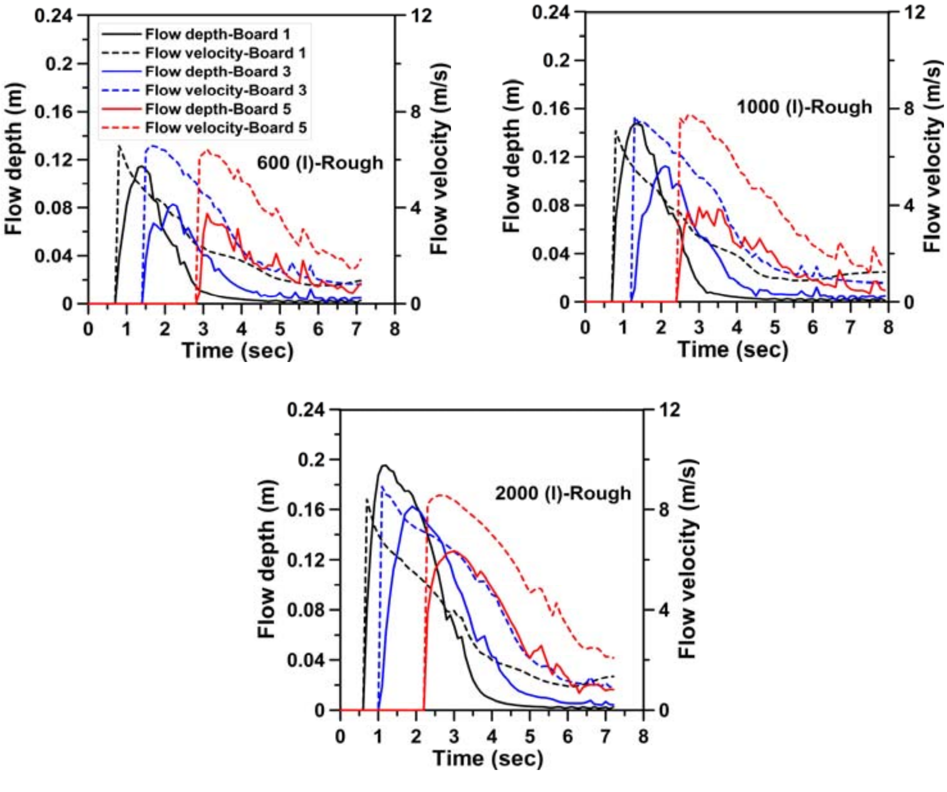

Figure 4: Flow depths and flow velocities for different overtopping volumes

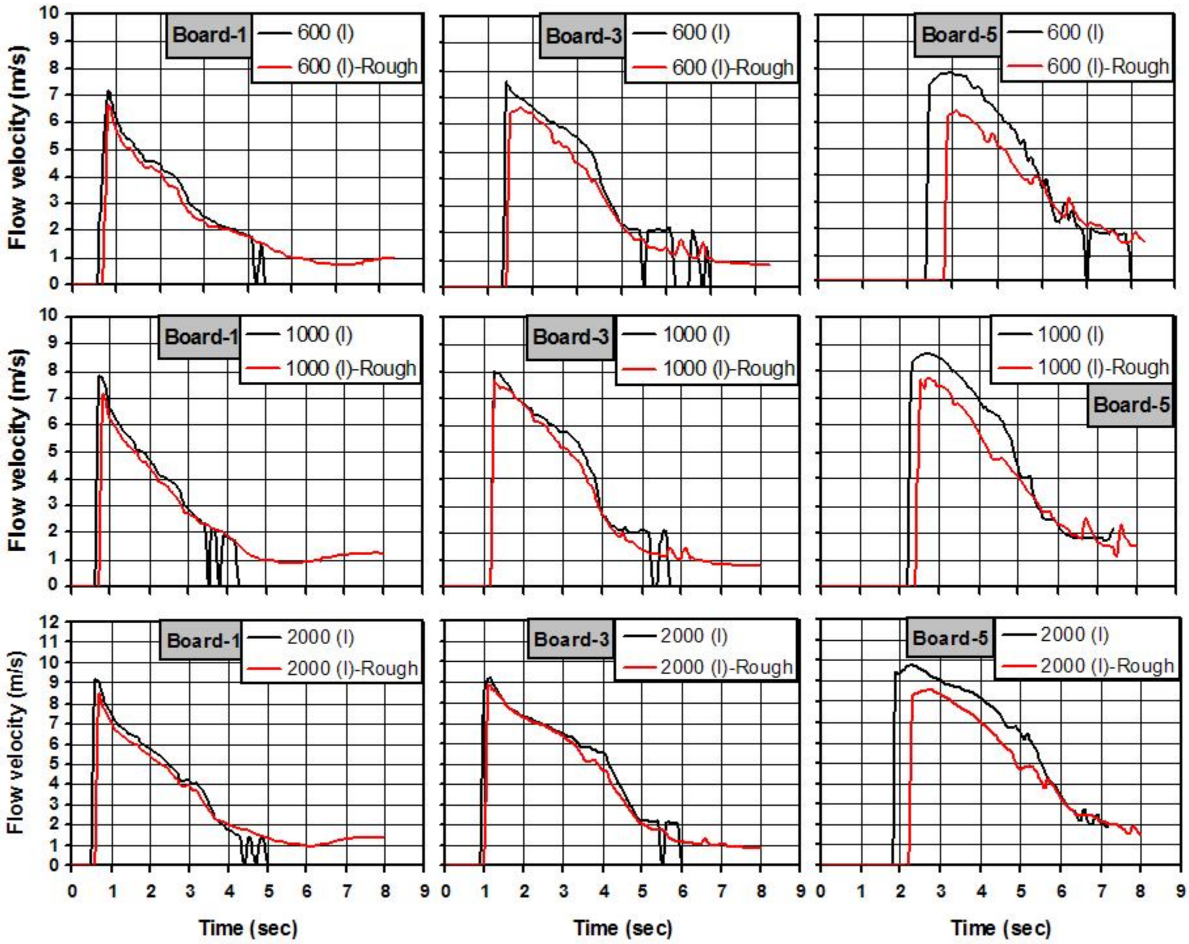

Figure 5: Variation of flow velocity with time at various locations

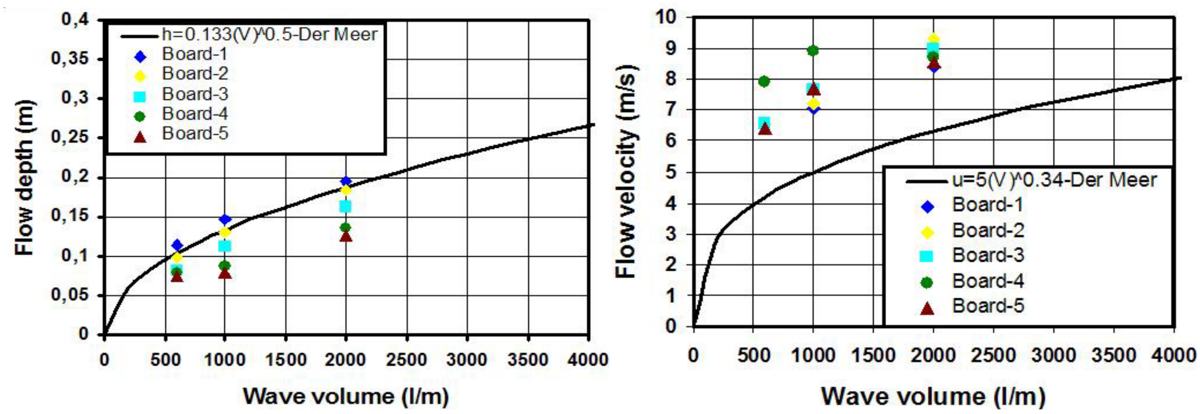

Figure 6: Variation of maximum flow depth and velocity with wave volume

4. CONCLUSIONS

Wave overtopping and the propagation of the waves on the crest and the landward side of a coastal dike is investigated numerically. Wave overtopping conditions are simulated using the concept of the Wave Overtopping Simulator. The RANS equations in conjunction with a turbulence model of the k-ε type and the VOF method are solved numerically, for "tracking" the free surface and the head of the "current" from the dike crest to the toe of the landward dike slope. The effect of grass cover is accounted for in the computations using an "equivalent roughness". Computed results are compared against proposed empirical relationships based on available field measurements of Van der Meer et al (2010). The following conclusions can be derived:

(a) The Numerical simulator for wave overtopping coastal dikes and wave propagating along the crest and the landward slope of the dike has been tested for three overtopping volumes and smooth and rough surface with promising results.
(b) The calculated maximum flow depth at the dike crest and for the three wave volumes considered is in agreement with an empirical relationship, proposed by Van der Meer et al (2010), based on field measurements with the wave overtopping simulator.
(c) The calculated maximum flow velocities at the dike crest and the landward slope of the dike are higher than those calculated by the empirical relationship of Van der Meer et al (2010), however the difficulty in measuring the maximum velocity in the field as well as the omission of the air entrainment in the computations make such a comparison to be considered with caution.
(d) Numerical simulations accounting directly for vegetation effects, through extra terms in the momentum equations and the turbulence model, and for air entrainment are in progress and are expected to improve the results significantly.

5. ACKNOWLEDGMENTS

The support of the European Commission through FP7.2009-1, Contract 244104 - THESEUS ("Innovative technologies for safer European coasts in a changing climate"), is gratefully acknowledged.

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