Modelling highly turbulent wave overtopping flows over flood defences

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Yearly, tens of billions of dollars are spent worldwide on the construction and reinforcement of flood defences to protect low-lying coastal areas against flooding. Without a strong cover, any flood defence will wash away by the waves attacking the structure during storm events [1]. Waves approach the dike in relatively deep water and change their shape when they reach the dike. On the seaward dike slope, the wave breaks and the broken wave runs up the dike, overtops the crest and then runs down the landward slope (Figure 1). These highly turbulent overtopping waves may cause an intolerable amount of water overtopping at the dike and also exert high forces on the dike cover, which threaten the stability of the dike. Therefore, accurate estimates of the amount and the characteristics of the overtopping flow are essential for the design and safety assessment of flood defences [2].

Nowadays, wave overtopping flow is described using bulk flow properties such as depth-averaged velocities, shear stresses or other flow-averaged estimates. However, spatially and temporally varying processes, such as turbulence and flow accelerations have shown to be important flow characteristics that determine the forces on dikes. Wave overtopping flow is highly complex, with high velocities (up to 10 m/s), very high degrees of turbulence while the flow is intermittent, which complicates accurate measurements and numerical modelling.

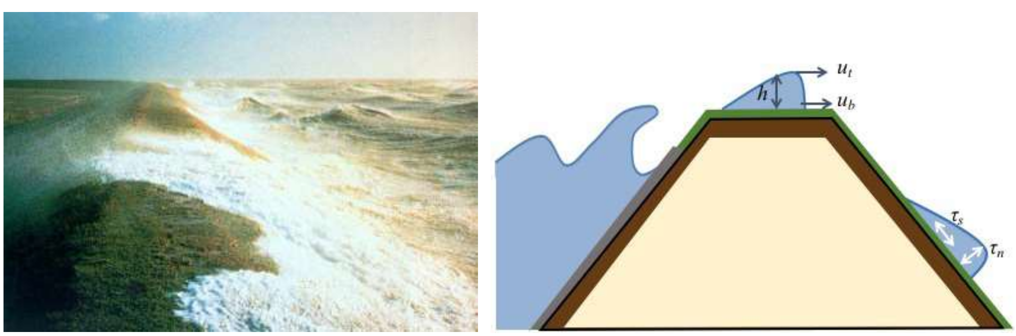

Figure 1: Waves approach the dike and break on the seaward dike slope. The broken waves run up the dike, overtop the crest and then run down along the landward slope. Left: photograph of grass covered dike during wave overtopping [5] (Picture courtesy: HR Wallingford). Right: Schematization of wave overtopping on a grass-covered dike. The overtopping flow has a layer thickness h, the flow velocity near the bed u_b and the flow velocity in the top layer u_t. Typical layer thickness and velocities range between 1-50 cm and 1-10 m/s respective. The waves pull on the grass cover with a shear stress τ_s parallel to the dike surface and a normal stress τ_n perpendicular to the dike surface (figure adapter after [4]).

With our research, we aim to increase the fundamental understanding of the flow processes and the forces that these complex flows exert on the dike covers. The characteristics of the wave overtopping flow depend on the wave characteristics, the geometry of the dike cover, local changes in the surface roughness and small-scale irregularities in the dike cover. Berms and roughness elements are often applied on dikes to effectively reduce the amount of overtopping. Detailed physical model tests are very expensive and time-consuming, and there are many variables that are hard to measure. Therefore, a numerical model has been developed to study these flow processes in detail for a wide range of wave characteristics and dike geometries.

The numerical wave overtopping model is developed in the open-source software OpenFOAM®, which solves the two-phase Reynolds-averaged Navier–Stokes equations using the Finite Volume method. For the turbulence, the k-ω SST model has been selected which accurately solves the turbulence in both the free-stream region and the boundary layer. The mesh consists of quadrilateral grid cells oriented parallel with the slope surface with a resolution of 10 mm in horizontal and vertical directions on the seaside slope and 20 mm on the crest and landward slope, both coarsening upwards. The model has been calibrated and validated on flume experiments [3] and field tests [4] and subsequently has successfully been applied to predict the amount of wave overtopping for highly complex dike configurations and to estimate the time and location dependent forces on the dike cover during wave overtopping [4].

Numerical modelling of wave run-up and overtopping at the seaward slope

Flume experiments were carried out in the Pacific Basin at Deltares (Figure 2a). Data from these experiments are used to improve existing empirical overtopping equations [3] and as validation data for the numerical model for wave overtopping discharge. These experiments showed that the effect of roughness is not constant, but varies with respect to the wave characteristics and dike configuration. New equations for berm and roughness influence factors have been developed that show a significantly better performance on estimates of the overtopping discharge within the tested range compared to existing formulae [3,6].

The range of dike configurations and wave conditions in these experiments was limited. Therefore, the numerical OpenFOAM model was developed and applied to these experiments to extend this range. The model was successfully calibrated on the experimental data and was capable of accurately predicting the average overtopping discharges at dikes with the accuracy within a factor of 2 of the experimental overtopping discharges. This validated model is now used to study the effects of different sizes of the seaward berm, the effect of the still water level and varying roughness and angles of the seaward slopes. This research also shows that placing revetments (each with a different roughness) at different elevations on the seaward slope can contribute differently to the overall roughness factor. Roughness elements on the upper slope are the most effective in reducing wave overtopping compared to the roughness elements on a berm or on the down slope. This research enables optimizing the dike design while maintaining the flood protection function of the dikes.

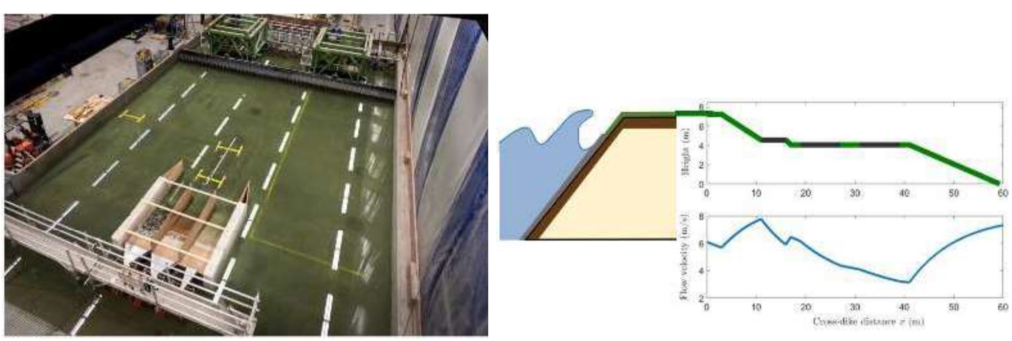

Figure 2: Left: Flume experiments in the Pacific Basin at Deltares to quantify the effect of a berm and revetments on overtopping discharge [3] (Picture courtesy W. Chen). Right: Results of the analytical model [7] to simulate flow velocity and layer thickness along a complex landward slope [1] .

Numerical modelling of wave overtopping at the landward slope

An analytical model has been developed to predict the maximum flow velocities along the landward slope [7] (Figure 2, right). This model gives accurately predicted flow velocities for a range of wave characteristics and dike geometries. The flow velocity is often used as input for dike erosion estimates [5]. However, turbulence in the wave overtopping flow caused by sudden changes in surface roughness, the slope angle and irregularities of the dike cover also affects dike cover erosion. It is still extremely challenging to measure turbulence in these high velocity, intermittent flows. Therefore, the numerical OpenFOAM model was developed and applied on the crest and landward slope of dikes (Figure 3, right), to more accurately quantify the characteristics of the overtopping flow. The OpenFOAM model was able to reliably predict shear stresses, normal stresses and pressures in the overtopping flow [4]. Application of the model to complex landward slopes (Figure 2, right) showed that the pressure increases up to a factor of 6 at transitions in the slope. The pressure increase from the crest to the landward slope can be related to the separation and reattachment with the slope of the overtopping flow leading to a high impact. High pressure at the inner toe, where the slope changes to a horizontal plane, are caused by jet formation related to the slope change. This new numerical model is a useful tool to quantify the erosion inducing stresses along the dike surface to locate the weak spots for cover failure and improve the design of grass-covered flood defences [4].

Figure 3: Numerical simulation of waves running up the dike with a berm and cause wave overtopping (Left). Overtopping waves run over the crest and cause high shear and normal forces due to the high velocities and turbulence (Right).

The future of numerical wave overtopping modelling

The numerical OpenFOAM model has been developed to better understand the impressive power of overtopping waves and their effect on the strength of our flood defences. The numerical modelling tool enables to identify the most important flow processes, which will contribute to the further development of design rules and guidelines for climate-proof flood management. In addition, uncertainties need to be quantified and included in new probabilistic risk frameworks to be able to probabilistically predict the strength of dike covers. In collaboration with Rijkswaterstaat, and Deltares, the developed knowledge and tools will be implemented into practical design tools.

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