Modelling wave overtopping for flood defense reliability

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Abstract

Failure of dike covers due to wave overtopping erosion may initiate dike breach. Surface transitions in the dike cover, such as cure points, height difference, roughness difference and objects are often weak spots, but the effects of such transitions on the wave overtopping discharge and associated location and evolution of dike cover erosion are highly uncertain. Dike cover erosion is dominated by the turbulence-dominated shear stress at the jet front. Therefore, a detailed numerical Finite Element model was developed. In this paper the preliminary results of the model of Aguilar-Lopez (2016) and Bomers et al. (2018) are briefly presented. At the University of Twente, two PhD students recently started on the challenge of quantifying the effect of transitions in grass covered dikes on dike erosion. In this paper, we present their research plans.

1 Introduction

Two-thirds of the Netherlands is endangered of flooding without dikes (Van der Meer et al., 2016). These highly populated areas are protected by the Dutch flood defense system, where earthen dikes are one of the main flood defense structures. However, the sea level rises and peak river discharges increase due to climate change, calling for more powerful flood defenses. A combination of high water levels in combination with increased wave heights during storms causes waves to overtop the dikes (Figure 1). Wave overtopping is one of the main mechanisms causing dike breach (Sharp et al., 2013). Waves that overtop the dike crest, run down on the landward slope and cause erosion on the landward side of the dike. Frequent wave overtopping results in erosion of the dike cover. Once the cover is eroded, the core material of the dike structure starts to erode resulting in weakening of the dike and in the end in a dike breach (Oumeraci et al., 2005).

Surface transitions in the dike cover, such as cure points, height difference, roughness difference and objects are often weak spots (Dean et al. 2010, Van der Meer et al. 2014), but the effects of such transitions on the wave overtopping discharge and associated location and evolution of dike cover erosion is highly uncertain.

Figure 1. Wave overtopping of a grass covered dike at Hartlepool, UK. Picture courtesy: HR Wallingford.

A classification of transitions in grass covers of dikes is presented by Van Steeg and van Hoven (2013). Transitions in grass cover on dikes can be classified based on location, cover type, and geometry. The slope on the water-side is usually enforced with stones or asphalt to withstand the forces of the waves and currents. In this case, a transition in cover type and associated roughness occurs at the slope: from grass to stone or to asphalt. Another common transition in cover type is the transition from grass to embedded objects on the water- or land-side slope, for example stairs, benches or trees. Also changes in inclination are a type of transitions, classified as geometry transitions. The change in inclination can be convex or concave. Finally, the orientation and height difference are classes of transitions.

In this paper, we show the preliminary results of a numerical model applied to a grass-road transition (section 2) and identify challenges for further research. In section 3 a research plan is presented that will be executed at the university of Twente in the next 4 year with the aim to quantify the effect of transitions in grass covered dikes on dike erosion.

2 Numerical dike cover erosion model

2.1 Model description

Bomers et al. (2016, 2018) and Aguilar-Lopez (2016) developed a detailed numerical model to predict dike cover erosion using coupled hydrodynamic and erosion modules (Figure 2). The model simulated erosion due to waves with different volumes that were released on the dike crest. Firstly, the hydrodynamic model simulates the wave overtopping flow to compute the bed shear stress. Subsequently, an erosion model computes the erosion depth along the crest and landward slope to update the dike profile. In case the erosion depth reaches the critical value, the hydrodynamic model recomputes the overtopping flow, using the updated dike profile.

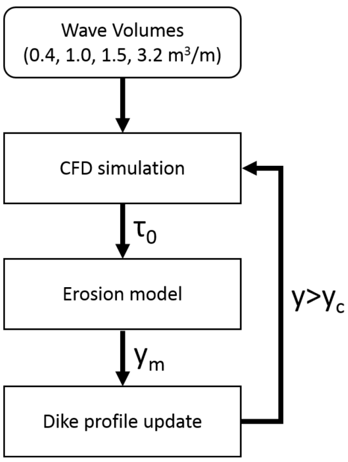

Figure 2. Schematic overview of the dike cover erosion model. Adapted after Bomers et al. (2018).

The model is validated on an experiment near the village of Millingen aan de Rijn in the Netherlands with the Wave Overtopping Simulator (WOS) for a dike section with a road on the crest (Figure 3).

The 2DV unsteady hydrodynamic model consisted of a CFD simulation using the commercial COMSOL Multiphysics software. In the 2-phase CFD simulation, the Reynolds-Averaged Navier Stokes equations were solved with a k-ε turbulence model using a Finite Element Method. The wave overtopping simulator (WOS) was explicitly schematized in the CFD model. Roughness of the road and roughness of the grass cover were set according to Chow (1959).

The model grid consisted of 13000 finite elements, with a refined grid of 2.3mm grid cells near the bed. The model boundary conditions consisted of a range of volumes between 0.4 and 3.2 m3/m in the WOS tank, released at time t=0.

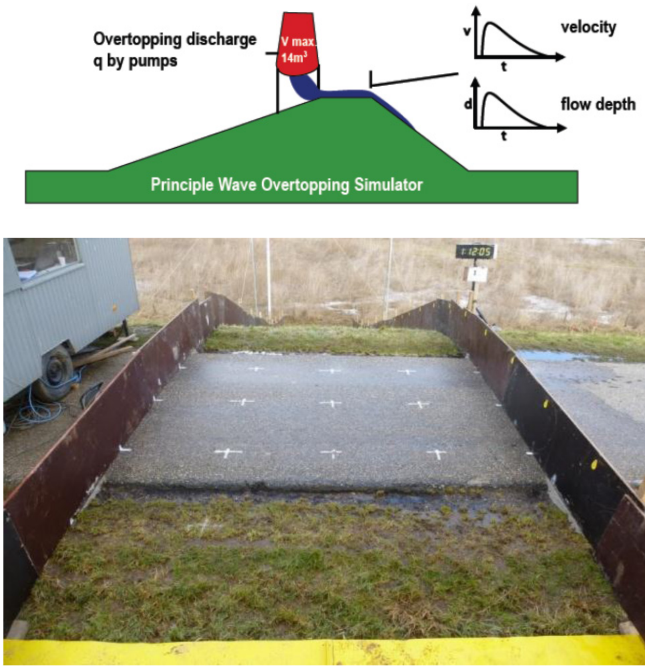

Figure 3. Top: principle of the Wave Overtopping Simulator (WOS). Bottom: test section of the dike with the road on top, looking downstream. (Picture courtesy: Van der Meer et al. 2009, top; Bakker et al. 2013, bottom).

The erosion model is based on the turf-element model presented by Hoffmans (2012), extended for depth, d>0.1m by Valk (2009). The local erosion depths are computed based on depth-averaged velocity and includes the grass and clay quality in the soil parameter:

$$y_m = \frac{(\omega^2 \tau_0 - \tau_c(d)) \times t_{wave}}{E_{soil}(d)} \quad (1)$$

where y_m is the amount of scour due to a single overtopping wave [m], τ_0 the bed shear stress [N/m^3], τ_c the critical bed shear stress [N/m^3], which depends on depth, d [m], t_{wave} the overtopping time [s], E_{soil} the soil erosion parameter [m/s] and ω the turbulence coefficient [-], which accounts for the turbulence generated by surface friction (Hoffmans 2012). More information about the model is given in Bomers et al. (2018).

2.2 Model validation

The numerical model was preliminary validated on the dike experiment using the wave overtopping simulator at Millingen aan de Rijn. Figure 4 shows a snapshot of the simulated velocity of the overtopping wave.

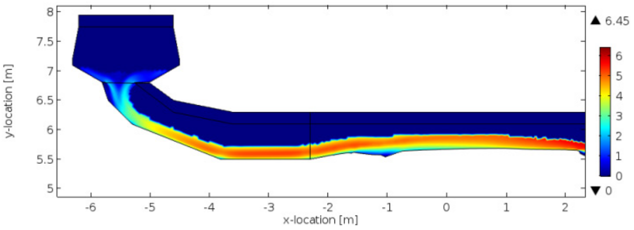

Figure 4. Flow velocity [m/s] of the overtopping flow at t=1.7s after release of volume, V=1.5 m3/m (Bomers et al. 2016).

Table 1 shows the validation of the overtopping flow velocity and layer thickness at the crest and at the slope. In general, the hydrodynamic model results are in the correct order of magnitude. Small differences at the slope show a slight underestimation of the velocity and corresponding overestimation of the layer thickness. Further calibration of the model parameters can improve the model performance, but the results were considered sufficiently accurate to predict erosion trends. Figure 5 shows the turbulence intensity of the overtopping wave from the model. No data was available to validate these results, but generally high turbulence is observed at locations with changing slopes (e.g. at the shoulders of the road) and turbulence increases along the landward slope as expected.

The predicted erosion profile along the dike crest and land-side slope showed a similar trend as the observations (not shown). The largest scour depths were observed and simulated (Figure 6) directly downstream of the road, which can be explained by the large turbulence. Figure 5 shows the average turbulent erosion potential $\overline{\boldsymbol{U}(t)\boldsymbol{k}(t)}$, which is not a physical parameter, but a way to show the visualize the most vulnerable spots. On the landward slope, the scour depth increased towards the toe of the dike, due to increasing flow velocities and associated turbulence intensity. In summary, both the location and order of magnitude of the scour along the crest and slope were simulated with reasonable accuracy. However, these results were obtained for only one case and further testing on other dike configurations and transitions is required.

Table 1. Comparison of observations (obs) and simulation (sim) of the hydrodynamic model for near bed velocity (u) [m/s] and layer thickness (h) [m] at two locations (outlet: x=-2.4 and slope: x=4.7, see fig. 5) along the dike profile for three wave volumes (V_{wave}).

V_{wave} (m^3/m)	Location outlet				Location slope			
	u_{obs}	u_{sim}	h_{obs}	h_{sim}	u_{obs}	u_{sim}	h_{obs}	h_{sim}
0.4	3.4	3.0	0.13	0.1	4.5	4.4	0.02	0.03
1.0	4.6	3.8	0.18	0.16	5.1	5.1	0.06	0.10
1.5	4.8	4.1	0.20	0.19	5.6	5.6	0.10	0.13

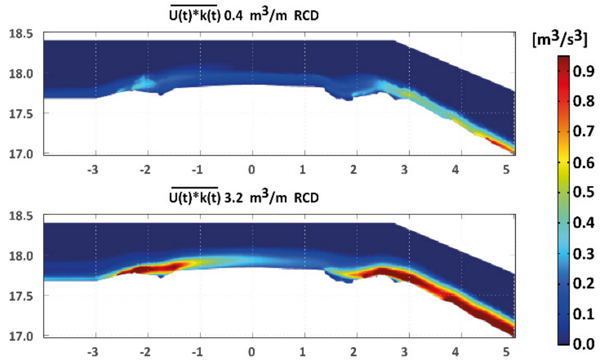

Figure 5. Average turbulent erosive potential ($\overline{\boldsymbol{U}(t)\boldsymbol{k}(t)}$) for the volumes V=0.4 and V=3.2 m3/m, with U is depth-averaged velocity and k=turbulent kinetic energy (Aguilar-Lopez 2016).

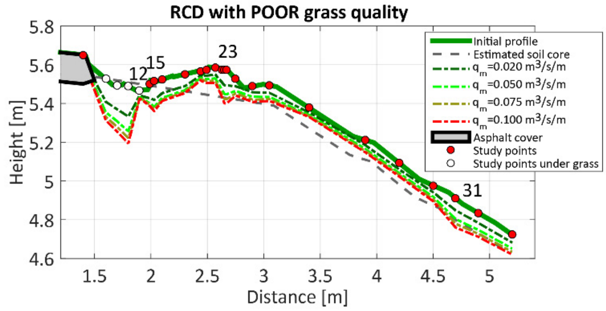

Figure 6. Erosion profiles for the different volume experiments (Aguilar-Lopez 2016).

2.3 Modelling challenges

The coupled hydrodynamic-erosion model shows promising results for the validation case study. However, several challenges remain.

Firstly, the availability of validation data was limited and of varying quality. Although, observations from several location along the dike profile were available (Bakker et al. 2013) the gaps and inconsistencies in the velocity and layer thickness data made a reliable validation or model calibration difficult. In addition, the validation on only near-bed velocity, measured using a paddle wheel, was available for validation. Near-bed velocity is only a proxy for the accuracy of the turbulence dominated bed shear stress. Therefore, accurate measurements of the detailed flow field (including turbulence and air entrapment) during an overtopping wave with constant volume would be beneficial for proper model validation. To our knowledge such detailed measurements are not yet available.

Secondly, the model was only applied for a road transition, while many more types of transitions are possible (Van Steeg and van Hoven 2013). Several field experiments have been carried out using the WOS to study the effect of different types of transitions. These experiments show that different transitions (e.g. grass-road, slope changes, roughness changes, grass-tree or grass-staircase (Steendam et al. 2014)) show different behavior. Insight into the effect of different types of transitions on the flow during wave overtopping is therefore a necessary first step into understanding their effect on dike cover erosion.

Thirdly, the question remains if the selected erosion model is suitable for other types of transitions. Using a shear stress-based method for dike cover erosion assumes that the dike cover is eroded in incremental layers of soil (slit erosion). However, observations during field experiments show that especially near transitions from grass to hard structures (e.g. a reduced lateral strength of the grass layer) the bed shear stress-based models might be less suitable and impact-based models might be more appropriate. This calls for an analysis of the applicability of the variety of existing erosion models (e.g. velocity-based, shear stress-based, or work-based) and probably requires extending the existing erosion equations for different types of transitions.

3 Research project: quantifying the effect of transitions on dike cover erosion.

At the University of Twente, two PhD students recently started on the challenge of quantifying the effect of transitions in grass covered dikes on dike erosion. In this section, we present their research plans.

Both PhD students (Chen & Van Bergeijk) work in the framework of the recently granted All-Risk research program: implementation the new risk-based standards in the Dutch Flood Protection Program (HWBP). This program is a joint effort of 6 Dutch Universities (18 researchers) to generate knowledge to support the implementation of the fully probabilistic risk-based flood protection strategy in the Netherlands. The topic of PhD1 is to assess the impact of transitions on wave overtopping characteristics using field and flume experiments. PhD2 focusses on the numerical modelling of this phenomenon. The objective of this research project is to develop tools for the safety assessment of dike cover erosion for a range of grass types and transitions.

For this study, we defined the following research questions:

1: What is the effect of transitions, such as variations in roughness and permeability of the dike cover on the rate of overtopping and overtopping flow characteristics?

2: How do vegetation quality and transitions affect the scour of the dike cover in flume and/or field experiments?

3: How well can a detailed numerical model predict dike cover erosion for a range of grass cover states and transition configurations?

4: To what extend can innovative technical measures and maintenance strategies increase the stability of the dike cover: locally around transitions, and for the dike as a whole?

The resulting modelling tool can be applied to evaluate measures to minimize erosion, provide maintenance guidelines and provide a tool for probabilistic dike safety assessment. Currently, the failure probability of transitions in the dike cover cannot be assessed, because the required tools do not exist.

Acknowledgements

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