MODELLING WAVE OVERTOPPING FOR GRASS COVERS AND TRANSITIONS IN DIKE REVETMENTS

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Transitions in the dike revetment or in the grass cover can significantly affect the wave overtopping discharge and the dike cover erosion. At the University of Twente, two PhD students recently started on the challenge of quantifying the effect of (1) waterside transition on the wave overtopping discharge and (2) transitions in grass covered dikes on dike erosion. In this paper we present their preliminary results and outline their future plans. Firstly, new laboratory experiments show that the existing wave overtopping formulas are not able to accurately predict the overtopping discharge in case of transitions on the waterside slope. Secondly, the analytical dike cover erosion model shows that transitions in grass covers significantly affect the location of maximum flow velocity and potential dike cover erosion. In future work, detailed numerical models will be developed for both the waterside slope and the landward slope to further increase our understanding of the effects of transitions on the wave overtopping discharge and the dike cover erosion.

Keywords: wave overtopping, flood defense reliability, grass cover erosion, revetments, transitions, erosion

INTRODUCTION

Failure of dike covers due to wave overtopping erosion may initiate dike breach (Figure 1). For this reason, it is important to accurately predict the wave overtopping discharge and the resulting dike cover erosion. Transitions in geometry (e.g. berms) and transitions in cover type (e.g. dike revetments and roads on a grass cover) significantly affect the wave overtopping discharge and dike cover erosion. However, the effects of transitions on the waterside slope on wave overtopping discharge and the effects of transitions in grass covers on wave overtopping erosion are largely unknown.

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

Transitions

Dikes are no longer solely used for flood safety, but have an increasing number of other functions such as recreation, transportation and nature. This results in an increase in both the number and the types of transitions on dikes. In this study, we differentiate between geometrical transitions and transitions in cover type. Both types of transitions occur on the waterside slope, the crest and the landward slope of the dike. Transitions affect the hydraulic load on the cover, the flow velocity and the cover strength, such that the overtopping discharge and the dike cover erosion are significantly influenced by transitions.

Geometrical transitions influence the hydraulic load, but have little influence on the strength of the dike cover. Examples of geometrical transitions are slope changes, berms and cure points. On the waterside slope, the load increases from the berm to slope. Although this transition has only a small effect on the stability of the cover (Chen et al, 2018), the increasing load results in the maximal observed erosion at this transition (Steendam, 2016). An increase in the hydraulic load was also observed from the landward slope to a horizontal crest because the flow wants to continue in the

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downward direction, often leading to a scour hole in case of grass covers (Steendam et al, 2014; Van Bergeijk et al, 2018). Measurements have shown that the grass cover strength was not reduced at this transition (Steendam et al, 2014).

Transitions in cover type affect both the hydraulic load on the cover and the strength of the cover. The change in bed roughness increases the hydraulic load by creating extra turbulence (Bomers et al, 2018). In case of transitions from grass to another cover type, the strength of the grass cover is reduced because the grass cover is unattached on one side. A board is located between two types of revetments on the water side slope to increase the stability of the blocks (Chen et al, 2018). Subsidence of the soil can result in a split of the board leading to a reduced cover strength. At the same time, the wave pressures against the revetment blocks are higher due to insufficient drainage leading to an increasing load at this transition.

Research gap and plan

Experiments and numerical models have shown that transitions are weak spots along the dike (Steendam, 2014; Bomers et al. 2018; Aguilar-López et al. 2018). The increase in the hydraulic load and the reducing cover strength makes transitions vulnerable for dike cover erosion. However, revetments and berms can be effective measures for reducing the overtopping discharge and the flow velocity.

A reliable prediction of the overtopping discharge is essential for the design and safety assessment of dikes and breakwaters. Several empirical equations exist to predict the average overtopping discharge (Hebsgaard et al. 1999, Etemad-Shahidi and Jafari 2015, TAW 2002, Capel 2015, EurOtop 2016) including the influence of the roughness of the waterside slope and the influence of berms. However, these equations are not sufficiently validated for waterside slopes with combinations of revetments. Therefore, laboratory experiments have been conducted to study the effect of transitions, such as roughness elements on berms, on the wave overtopping discharge.

Surface transitions in the grass cover, such as cure points, height difference, roughness difference and objects are often weak spots (Steendam et al. 2014), but the effects on the location and evolution of dike cover erosion is highly uncertain. Dike cover erosion is dominated by the turbulence-dominated shear stress at the jet front (Aguilar-Lopez et al. 2018). Therefore, a detailed FEM model was developed with a sufficiently accurate turbulence model (Bomers et al. 2018). However, such detailed models require high computational resources. Therefore, an analytical model is developed to predict maximum flow velocities continuously along the dike profile. This model enables a fast evaluation of 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 (1) waterside transition on the wave overtopping discharge and (2) transitions in grass covered dikes on dike erosion. The wave overtopping discharge is an essential input parameter to determine the grass cover erosion. In this way, accurate prediction of the overtopping discharge will lead to improved prediction of the dike cover erosion. Better understanding of the effects of transitions on the overtopping discharge and the dike cover erosion can lead to improved dike design and more accurate safety assessments of dikes. In this paper, we present the preliminary results of the two projects and outline the future plans.

THE EFFECT OF WATERSIDE TRANSITIONS ON THE WAVE OVERTOPPING DISCHARGE

Physical model tests

To investigate the influence of transitions on the waterside slope, such as a berm and roughness differences, on the average overtopping discharge, physical model tests have been performed in the Pacific Basin (at Deltares). This basin is large enough to allow three sections to be tested at the same time. The width of each section is 1 m and wooden boards were installed between the sections to avoid lateral influence of adjacent sections. Irregular waves were generated based on the JONSWAP in this experiment. Three wave gauges in front of the tested models were used to measure the wave elements. Three boxes were placed behind the models to collect the overtopped water. The total volume of the overtopped water of each test was determined by measuring the variation of surface water in the overtopping box using a wave gauge. To study the roughness influence on the overtopping discharge, four types of roughness elements are adopted in the tests, i.e. blocks with protrusion, blocks with open space, rocks and smooth slopes representing asphalt or grass (Figure 2). In addition, combinations of different types of roughness elements have also been tested. Both straight slopes without a berm and slopes with a berm were tested in this experiment program to investigate the berm influence. A slope gradient of 1:3 was used for the straight slopes. For the cross-sections with a berm, the gradient of the upper and lower slope was also 1:3. The berm width of 0.2 m was kept constant for all the sections with a berm. For each cross-section, the freeboard, water level, wave height and period were varied, resulting in nearly 410 tests in total.

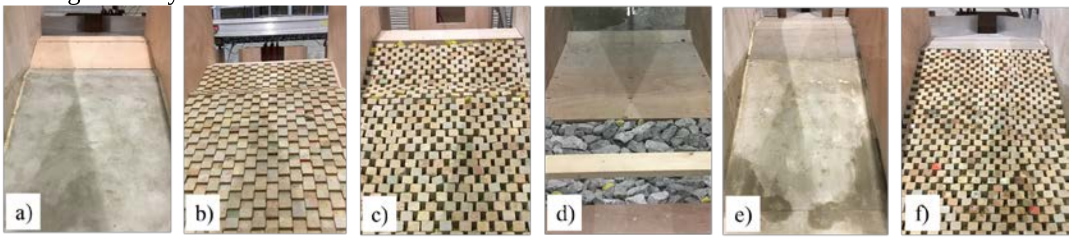

Figure 2. Six test sections illustrating the different revetments: from left to right with a) smooth slopes with a berm, b) protruding blocks on the slopes with a berm, c) open blocks on the slopes with a berm, d) rocks on the upper slope and berm, e) smooth straight slope and f) open blocks on the straight slope.

Preliminary results

The berm influence and the roughness influence factors are calibrated based on the overtopping equation to study the influence of a berm and the bed roughness on the average overtopping discharge. Existing overtopping formulae are examined for predicting dimensionless average overtopping discharges of smooth straight slopes to determine which overtopping equation to be used,. Overtopping equations given by Hebsgaard et al. (1999), TAW (2002), Etemad-Shahidi and Jafari (2015) and Capel (2015) are compared (Figure 3).

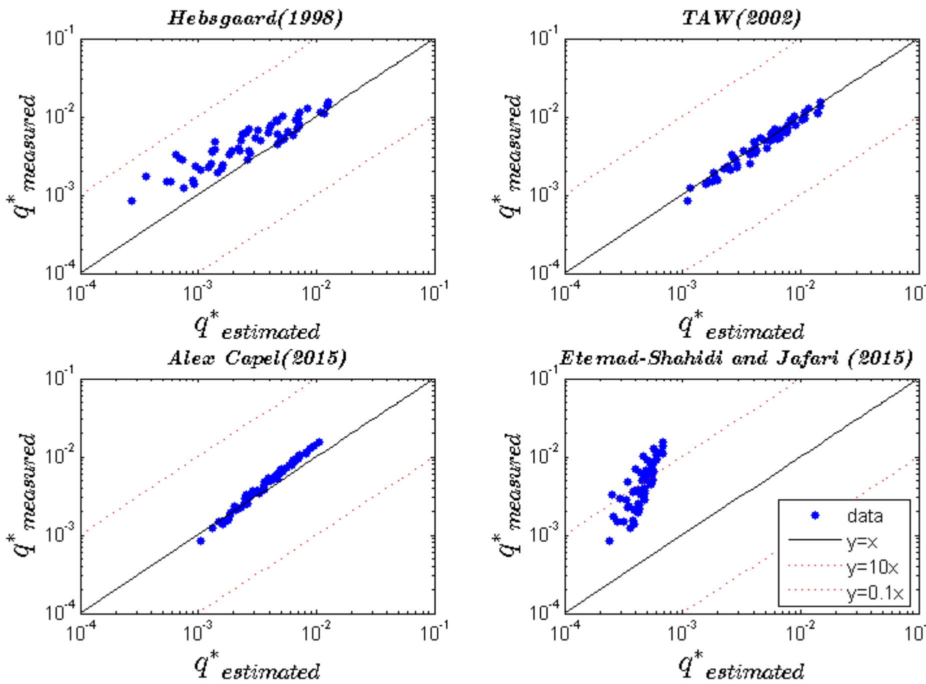

Figure 3. Estimation of the dimensionless overtopping discharge q^* using the existing overtopping formulas.

Figure 3 shows significant scatter between measured and calculated overtopping discharge using Hebsgaard et al. (1999) and Etemad-Shahidi and Jafari (2015) while overtopping equations by TAW (2002) and Capel (2015) result in a much better estimation of overtopping discharges and less scatter. Even though the Capel (2015) equation shows less scatter, it underestimates the overtopping discharge for larger values and slightly underestimates the discharge for smaller values. The TAW (2002) overtopping formulae perform well for predicting wave overtopping discharge for straight slopes without roughness elements. Therefore, we selected the TAW (2002) formula for further analysis.

The TAW (2002) provides default values for the influence factors for a large variety of roughness elements and equations to calculate the influence factors for berms. As a first step, we compared the measured overtopping discharges with the calculated discharges using the TAW (2002) formula including the berm factors and roughness factors calculated by the TAW (2002) methods (Figure 4). For smooth slopes with a berm, the data points (green squares) lie below the TAW (2002) overtopping equation line, which means that the TAW (2002) equation of berm factors underestimates the berm influence. Additionally, the overestimation of overtopping discharge for rough slopes covered by protruding blocks (blue cross) becomes larger as the overtopping discharge decreases. This might be because the TAW (2002) provided static values for the roughness factors, which cannot deal with the roughness influence well. Therefore, it is necessary to improve the estimation methods of the berm influence factors and the roughness factors to improve the performance of the TAW (2002) overtopping formulas.

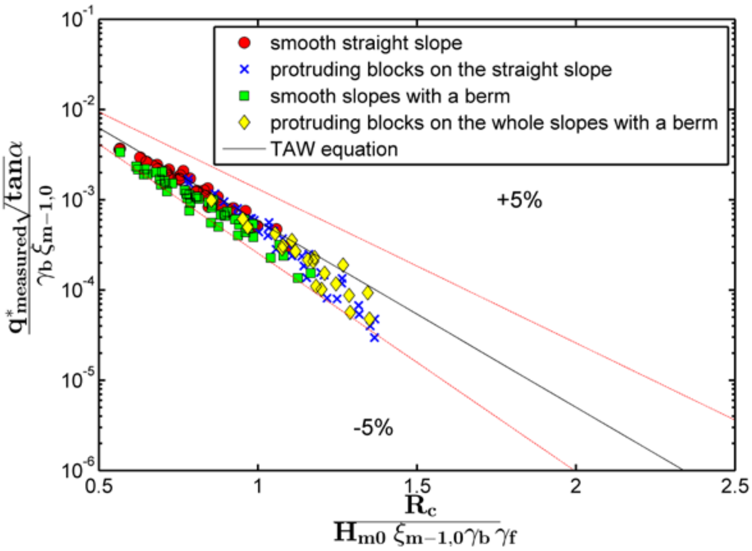

Figure 4. The measured dimensionless overtopping discharges versus the calculated values using the TAW (2002) equation. The envelope between the dashed lines shows the 90% confidence interval, according to TAW (2002).

Future work: improving the berm and roughness influence factors

Future work will focus on a detailed analysis of the experimental data to derive new formulas for the berm influence factor, the roughness influence factor and the combined influence of a berm and roughness. These new formulas are envisioned to accurately predict the wave overtopping discharge for combinations of berms and various types of roughness elements. Additionally, a detailed numerical model will be developed to extend the range of configurations beyond the experimentally tested range for further testing the validity of the newly developed formulas.

ANALYTICAL MODEL FOR THE FLOW AND THE EROSION ON THE LANDWARD SIDE

The amount and the location of the wave overtopping erosion depend on the overtopping discharge, the dike geometry and the cover type. An analytical model has been developed as a fast screening tool to determine the flow velocity and the dike cover erosion on the dike crest and the adjacent landward slope. The analytical model determines the variation in the maximum overtopping flow velocity and the erosion depth at any point along this cross-dike profile. The analytical model is computationally efficient and couples a newly developed analytical hydrodynamic model with an existing erosion model. This model uses the characteristics of the overtopping waves at the waterside crest line as boundary condition and computes the flow velocity along the crest and the adjacent landward slope. The model description together with an application to the Closure Dike in the Netherlands is provided in this section.

Hydrodynamic model

The analytical flow model calculates the variation in the flow velocity along the crest and landward slope. The model is validated with measurements of the flow velocity on the dike crest and slope from both flume and field test (Figure 5; Van Bergeijk et al, subm). The flow velocity at the start of the dike crest and the overtopping discharge are the two necessary boundary conditions for the model. These can be derived from measurements or empirical formulas based on dike geometry and wave conditions, for example the formula for the flow velocity reported by Van der Meer et al. (2011) or the TAW (2002) formula for the overtopping discharge. The analytical model is able to simulate transitions in geometry, such as slope changes and berms, and transitions in cover type, such as roads and revetments.

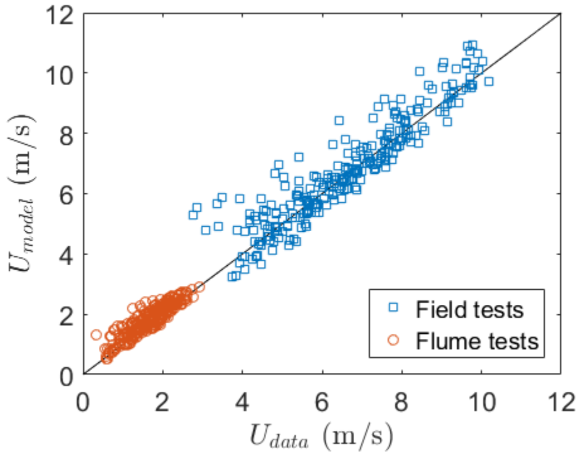

Figure 5: The modelled flow velocity U_{model} against the measured flow velocity U_{data} together with the one-to-one relation (based on Van Bergeijk et al. subm.).

Erosion model

The flow velocity along the cross-dike profile *U(x)* is needed for calculation of the erosion depth along the cross-dike profile. The erosion depth *z* is calculated using the erosion formula of Hoffmans (2012), where dike cover erosion occurs when flow velocity exceeds the critical flow velocity U_C:

$$z(x) = [(1.5 + 5\, r_0)\, U(x)^2 - U_C(x)]T_0 C_E, \qquad (1)$$

with the cross-dike coordinate x , the relative turbulence intensity r_0, the overtopping period T_0 and the strength parameter C_E. The critical flow velocity is a function of the cross-dike coordinate since it depends on the cover type and the quality cover (Hoffmans, 2012; Bomers et al, 2018).

Application: The Closure Dike

The analytical model is applied to the Closure dike in Netherlands to show that the model is able to combine several geometrical transitions and multiple cover types. The Lake Ijssel side of the Closure Dike consists of a grass-covered crest and slope with berms, biking paths and roads (Figure 6a,b). The flow model is run for the design conditions of the Closure Dike to investigate the possible erosion during the design storm. The Closure Dike is designed for wave heights of 4 m resulting in overtopping waves with a maximum overtopping volume of 2700 l and a maximum flow velocity of 6.1 m/s (Hoffmans and Jacobsen, 2014). The overtopping period was set to 4 s and the relative turbulence was set to 0.15, which is within the range reported by Bomers et al. (2018). The grass cover is of average quality (Hoffmans and Jacobsen, 2014), resulting in a critical flow velocity of 4.5 m/s and a strength parameter of $2 \cdot 10^6$ s/m (Verheij, 1995). It is assumed that the asphalt cover does not erode.

The modelled flow velocity decreases due to bottom friction on the horizontal parts while the flow velocity increases on the slope until a balance is reached between the gravitational acceleration and bottom friction (Figure 6c). The gradient of the flow velocity depends on the cover type since the bottom friction increases with increasing bed roughness. The berms along the profile reduce the flow velocity significantly resulting in no erosion of the grass cover in the middle of the roads at a cross-dike distance of 30 m (Figure 6d). This means that berms are effective measures in reducing the dike cover erosion. The erosion depth is slightly overestimated by the model. During a storm, more than 1000 waves will overtop for the design conditions resulting in an erosion depth of almost a meter. The predicted erosion depth with the model is higher than the prediction using the conservative calculation methods for dike assessments in the Netherlands (WBI, 2017). The difference can partly be explained due to the fact that the overtopping waves during a storm have a wide range of overtopping volumes and flow velocities, most of them smaller than the maximum used in this example. On the other hand, the erosion model needs to be improved to accurately model the erosion along a dike profile that includes several transitions.

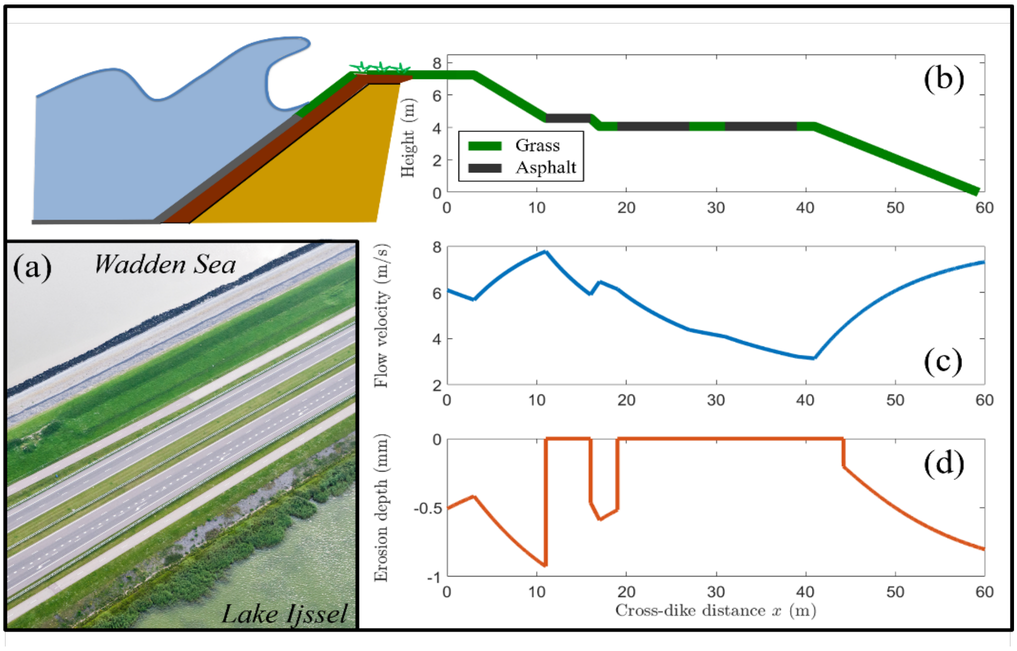

Figure 6: (a) Top view of the Closure dike. (b) The input profile of the Closure Dike. (c) The modelled flow velocity along the cross-dike profile, (d) The erosion depth after one wave along the cross-dike profile.

Future work: improving the erosion model

The current model calculates the erosion depth after one overtopping wave, but will be extended to the erosion depth after a storm. In addition, the erosion model is under development to incorporate the effect of additional turbulence created by transitions and the decreasing strength of the cover along transitions. These effects are important for accurately simulating the erosional effects of transitions (Hoffmans, 2014). Additionally, a detailed numerical model will be developed to understand the hydrodynamics of the overtopping wave and focus on the water flow around transitions.

CONCLUSIONS AND FUTURE WORK

In this paper we showed the preliminary results of two PhD students at the University of Twente on the effect of transitions in both the waterside and landward slope on wave overtopping and grass cover erosion. We conclude that:

- Laboratory experiments showed that the existing formulas are not able to accurately predict wave overtopping discharge in case of waterside berms and in case of different roughness elements on the waterside slope.
- The analytical model shows that transitions in grass covers significantly affect the location of maximum flow velocity and dike cover erosion. This model can be applied as a fast screening tool to identify locations at risk for wave overtopping erosion.

The next steps are:

- Developing new formulas for the berm influence factor, the roughness influence factor and the combined influence of a berm and roughness to accuratly predict the overtopping discharge.
- Extending the analytical erosion model on the landward side to include extra turbulence and reduced cover strength at transitions.

In future work, detailed numerical models will be developed for both the waterside slope and landward slope to further increase our understanding of the effect of transitions on wave overtopping discharge and dike cover erosion. A detailed turbulence closure model is required to accurately predict the additional hydraulic loads due to irregularities and roughness differences at transitions, both on the waterside and landward slopes. The numerical models of Bomers et al. (2018) and Aguilar-Lopez et al. (2018) indicate that enhanced turbulence at the transition from asphalt to grass may result in locally significant erosion. In future work, we will improve and further validate their numerical model and apply this to a range of dike configurations and transitions to improve our understanding of wave overtopping discharge and the erosion resistance of dike covers in the presence of transitions.

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