Dike cover erosion by overtopping waves: an analytical model

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Introduction

Climate change results in more extreme weather conditions such as storms and droughts. Droughts decrease the strength of the grass cover on dikes, which makes the dikes vulnerable to failure due to wave overtopping. During storms, waves overtop the dike and run down on the landward slope where the high flow velocities erode the dike cover. Experiments and numerical models have shown that erosion starts at the weak spots along the profile (Aguilar-López et al., 2018). One type of weak spots are transitions in dike geometry and cover type, for example the berm-road transition. These transitions decrease the strength of the dike cover while at the same time increasing the hydrodynamics load by creating extra turbulence (Bomers et al., 2018). In this study, three formulations for the turbulence in the erosion model are tested to determine the erosional effects of transitions due to turbulence.

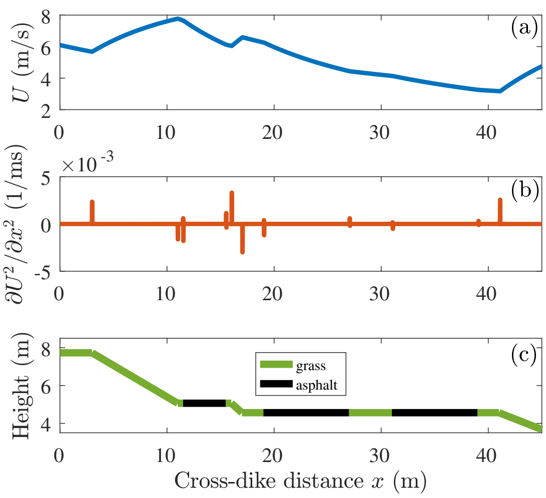

Figure 1: (a) The flow velocity U, (b) the flow velocity gradient $\partial U^2/\partial x^2$ and (c) the input profile of the lake IJssel side of the Afsluitdijk as a function of the cross-dike distance x.

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Test case: the Afsluitdijk

The coupled hydrodynamic-erosion model is applied to the lake IJssel side(Fig. 1c), because the profile contains several transitions in geometry and cover type: a berm with a biking path ($x \approx 13$ m) and another berm with two roads ($x = 18-40$ m). The Afsluitdijk is designed for wave heights of 4 m resulting in overtopping waves with a maximum overtopping volume of 2700 l and maximum flow velocity of 6.1 m/s at the start of the dike crest. The analytical formulas for the flow velocity of Van Bergeijk et al. (2018) are applied to the test case. The calculated flow velocity decreases due to bottom friction on the horizontal parts and increases on the slope until a balance is reached between the gravitational acceleration and bottom friction (Fig. 1a).

Erosion model

The flow velocity U along the cross-dike profile is used to determine the dike cover erosion. The analytic erosion model of Hoffmans (2012) assumes that erosion only occurs if the flow velocity U exceeds the critical flow velocity U_C. In this case, the erosion depth z_d (mm/wave) is calculated as

$$z_d(x) = \left[(1.5+5.0\, r_0)U(x)^2 - U_C(x)^2\right] T_0 C_E \quad (1)$$

with the cross-dike coordinate x, the turbulence intensity r_0, the overtopping period T_0 and the strength parameter C_E. Assuming an average grass quality, the critical flow velocity U_C is 4.5 m/s and the strength parameter C_E is $2 \cdot 10^{-6}$ s/m (Hoffmans, 2012). Furthermore, it is assumed that the asphalt covers of the biking path and the roads do not erode and the overtopping period is set to 4.0 s.

Turbulence parameter

Three formulations for the turbulence intensity r_0 are tested to determine how transitions affect the turbulence intensity and the erosion depth. The turbulence intensity is determined using (A) a constant value, (B) the formulas of Hoffmans (2012) and (C) turbulence input based on the flow velocity gradient (Fig. 2a).

Formulation A: Constant
In the first case, the turbulence intensity r_0 is assumed to be constant along the cross-dike profile. The value is set to 0.1 based on turbulence measurements on the slope of a river dike during overtopping tests (Bomers et al., 2018).

Formulations B: Hoffmans (2012)
Hoffmans (2012) derived two formulas for the turbulence intensity. On the horizontal parts of the dike profile, the turbulence intensity depends on the cover type as

$$r_0 = 0.85\sqrt{f} \qquad (2)$$

with f the bottom friction coefficient. The bottom friction coefficient is 0.01 and 0.02 for grass covers and asphalt covers, respectively. On the slope, the turbulence intensity is calculated as

$$r_0 = \sqrt{\frac{g\,q\sin\varphi}{U_{max}^3}} \qquad (3)$$

with the gravitational acceleration g, the discharge q, the slope angle φ and the maximum flow velocity U_{max} along the slope.

Formulation C: Velocity gradient
The flow velocity depends on the slope angle and the cover type, thus the double gradient of the flow velocity increases significantly at transitions (see Fig. 1b). The extra turbulence created by local acceleration and deceleration of the flow is simulated by increasing the turbulence intensity with 0.1 at locations where $\left|\partial U^2/\partial x^2\right| > 0$. The extra turbulence input is followed by a decrease in the turbulence intensity to 0.1 over a cross-dike distance of 1 m.

Results
The erosion depth along the cross-dike profile was determined for the three formulations of the turbulence intensity (Fig 2b). The difference in erosion depth between the methods is largest at the transitions ($x = 5, 11, 15-20$ m). The difference in erosion depth between a constant turbulence intensity and the formulas is very small. However, the erosion depth changes significantly using the velocity gradient method, especially around transitions. At the location of maximum erosion ($x \approx 11$ m), the erosion depth is 0.35 mm/wave larger in case of the velocity gradient method compared to the other two methods. Most erosion occurs around $x \approx 11$ m because the flow velocity is maximal (Fig. 1) and both the slope and the cover type change. The cover does not erode for $x > 20$ because the flow velocity does not exceed the critical flow velocity.

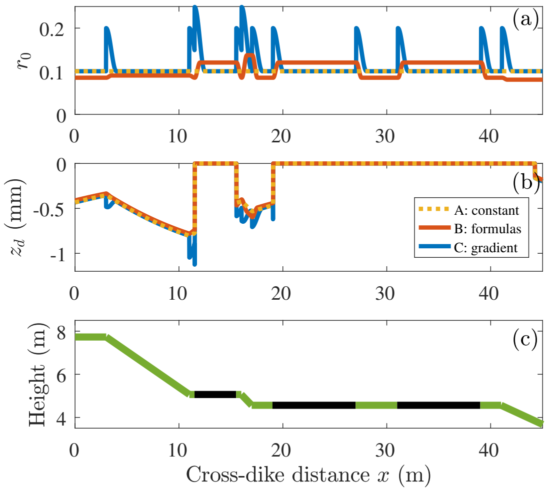

Figure 2: (a) The turbulence intensity r_0, (b) the erosion depth z_d and (c) the input profile of the lake IJssel side of the Afsluitdijk as a function of the cross-dike distance x.

Conclusions
Existing flow and erosion models need to be improved to understand the effect of climate change on the erosion resistance of transitions in dike covers. The load term in the dike cover erosion model of Hoffmans (2012) is adapted using three different formulations of the turbulence intensity. It was found that the turbulence intensity formulation at transitions significantly affects dike cover erosion. The analytical model proves useful as a first estimate to predict dike cover erosion. However, to create more realistic erosion profiles with smoother slopes, further testing of the turbulence formulation as well as formulations for the grass cover strength (U_C, T_0, C_E) are necessary.

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