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Research report:

EXPERIMENTAL SET-UP AND MODELLING TOOLS FOR THE LOAD BY OVERTOPPING WAVES IN EROSION MODELS

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Client:
Rijkswaterstaat

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Contents

1 Introduction

1.1 Context

The erosion process of the upper grass cover layer by overtopping waves is well understood and included in the Dutch Safety Assessment of dikes. However, knowledge is missing on the follow-up erosion processes that will eventually lead to a dike breach. Rijkswaterstaat wishes to increase the knowledge of these erosion processes, especially the effect of impact forces on the erosion process. Therefore, wave overtoppping erosion experiments will be performed on dike sections in the HedwigeProsperPolder on the border of Belgium and the Netherlands as part of the Polder2C's project. The results of this study are used for the design of these experiments and are a first step for the development of modelling tools within the erosion theme of the Polder2C's project.

1.2 Background

Wave overtopping is one of the main failure mechanisms of earthen flood defences. During a storm, high waves overtop the dike and flow down the landward slope. These overtopping waves exert an high hydraulic load on the cover of the flood defence leading to erosion of the cover material. Once the cover is eroded, the core material of the flood defence will erode leading to weakening of the flood defence and finally to a breach.

The dikes in the HedwigeProsperPolder consist of a sandy dike core with a cover layer of grass on top of a clay layer. The erosion process of these types of covers consists of two phases. During the initiation phase, the grass cover and top layer are eroded. This type of erosion is often described by scour erosion models such as the cumulative overload method (Van der Meer et al., 2010) and the analytical grass-erosion model (Van Bergeijk et al., 2021a). Once the cover is eroded, the erosion hole will deepen and migrate towards the crest. The deepening and migration of an erosion hole can be described using the head-cut erosion model of Natural Resources Conservation Service (1997) that was calibrated by Van Hoven (2014) for erosion by overtopping waves.

Previous wave overtopping experiments in the Netherlands and Belgium show two main locations of erosion on the landward side of grass-covered dikes: (1) the landward toe due to high flow velocities and (2) the upper slope as the result of wave impact. For steep slopes, the wave separates at the crest line and reattaches on the upper slope. This process is called wave impact (Ponsioen et al., 2019) and results in high normal forces at the location of reattachment (Figure 1a). These high normal forces can results in erosion and failure of the dike cover, where the location of impact depends on the slope steepness and the overtopping volume (Ponsioen et al., 2019; Van Bergeijk et al., 2021b). A similar process will occur when the cover is damaged as the result of animal burrowing or erosion. A vertical cliff forms at the start of such a damage where the wave will separate from the slope and impact in the damage (Figure 1b). The deepening of such a damage is mainly caused by the high hydraulic load at the impact location.

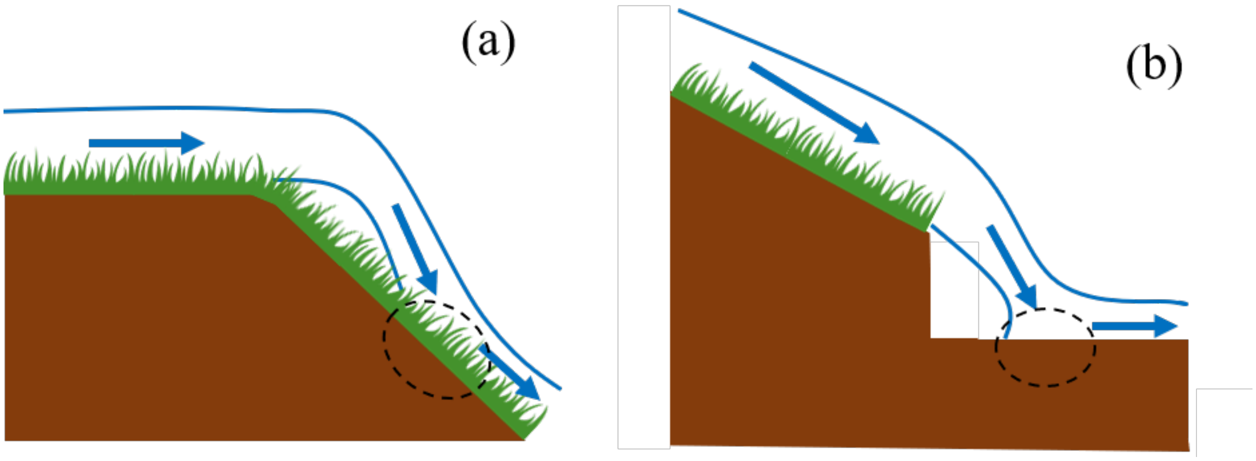

Figure 1: Schematization of the wave separation and reattachment on the slope for (a) wave impact at the transition from the crest to the landward slope and (b) a damage. The wave exerts high normal forces at the impact location indicated by the black dashed circle.

1.3 Motivation

In the Dutch safety assessment for dikes, the erosion by overtopping waves is calculated using the Cumulative Overload Method based on front velocities (van der Meer et al., 2015). This means that the effect of impact forces are not included in this method, since the impact forces are calculated using the normal stress.

Additionally, failure is defined as the exceedance of 20 cm erosion depth related to the top soil layer where the grass roots increase the strength of the clay layer ('t Hart et al., 2016). This means that the strength of the remaining cover layer and the dike core are not included in the safety assessment. The strength of the remaining dike material is called the residual dike strength, which is the ability of the flood defence to continue its water retaining function after it has failed according to the failure definition (Van Hoven, 2014). An extension of the currently used erosion models for overtopping is required to simulate the complete failure process from erosion onset to a dike breach. However, information is missing on the effect of damages on the overtopping load and on the strength of the remaining cover material.

Overtopping experiments help to determine the strength and the erosion rate of dike covers. The drawback of overtopping experiments is that the normal stress on the dike cover can not be measured during these experiments. Numerical models are a useful tool to obtain the hydraulic load on dike covers such as the flow velocity and the normal stress (Bomers et al., 2018; Van Bergeijk et al., 2020).

1.4 Project objectives

In this project, we use a numerical model to determine the hydraulic load by overtopping waves on the dike cover. The goal of the study is to develop modelling tools for the impact forces by overtopping waves and deliver a preliminary design of the planned overtopping experiments in the HedwigeProsperPolder. Four objectives are identified in this project:

I. Determine the conditions for wave separation and the impact location for wave impact on the landward slope.

II. Develop formulas for the maximum normal stress in an erosion hole and the impact location.

III. Provide an overview of the available erosion models for cover erosion by overtopping waves

IV. Design overtopping experiments in the HedwigeProsperPolder.

In this study, the hydraulic load is described by the flow velocity and the normal stress that is calculated for the dike profiles in the HedwigeProsperPolder using the numerical model. The load is determined in detail for the wave separation and reattachment process at the crest line and the impact at a damage. Analytical formulas are developed to calculate the impact location and the hydraulic load at this location. These formulas can be used to describe the hydraulic load in erosion models. The results related to the impact location are important for the design of the overtopping experiments.

1.5 Outline of this report

This report provides a short description of our numerical model in Section 2. Firstly, the numerical model is used to determine the volumes where wave impact will occur for the profiles in the HedwigeProsper Model (Section 3). Next, the model is used to determine the impact location and overtopping forces for an erosion hole. Section 4 provides a description of an analytical model to calculate the impact location that is validated with the results of the numerical model. The model results are also used to derive a relation between the normal stress and flow velocity that can be used in erosion models. Thereafter, we explain how the formulas for the hydraulic load can be used in the calculation methods for erosion in Section 5. Section 6 describes the design of the overtopping tests and how we can increase our knowledge on the erosion process using these tests. Finally, the conclusion are stated in Section 7.

2 Model description

We developed a 2D-vertical numerical model to simulate the overtopping flow over the crest and the landward slope of grass-covered dikes in the open-source software OpenFOAM ®(Van Bergeijk et al., 2020, 2021b). The model simulates the flow of one overtopping wave and provides detailed information on the hydraulic variables as function of time and location. The model simulations are performed in OpenFOAM v2012 on the Cartesius server of SurfSara. Output with a frequency of 100 Hz is required to obtain the hydraulic load as the result of wave separation and reattachment. This results in output of around 40 GB in OpenFOAM, which is reduced to around 90 KB after post processing in Matlab. The generation of the boundary conditions and mesh together with the post processing of the model output are described in more detail in the Appendix A and a full description of the model is given in Van Bergeijk et al. (2020).

The simulations in this study are performed for dike profile 6 in the HedwigeProsper-Polder (Figure 2). The model domain starts halfway the dike crest at a cross-dike distance $x = 0$ m. The measurements of the dike profile are used to generate an idealised dike profile with a crest width of 4.8 m, a slope steepness of 1:2.7 and a slope length of 18.4 m. An idealised profile is used since this type of grid is computationally more efficient and therefore saves computational costs. Moreover, a sharp change in slope angle from the crest to the slope is necessary to simulate the wave impact process. Additionally, the model results obtained with an idealised profile are generally applicable and less specific to dike profile 6. For example, the measured profile shows a small bump around $x = 22.5$ m which affects the results. The idealised profile does not have a significant effect on the models results and

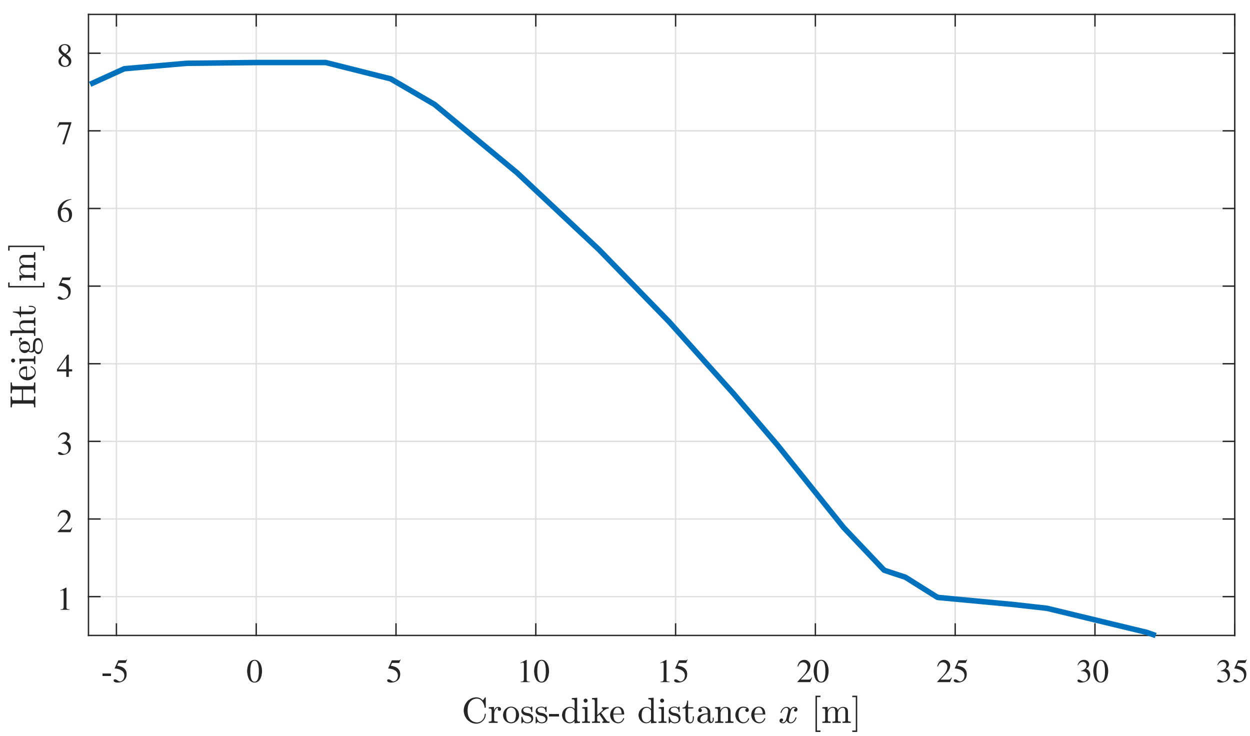

Figure 2: The dike profile used in the OpenFOAM simulations.

are therefore still applicable for the measured dike profile, as discussed in more detail in the Appendix A.

The grid size is set to 1 cm x 1 cm (cross-dike Δx x vertical Δz) and the turbulence is solved using a k-ω SST turbulence model together with a Nikuradse roughness height of 8 mm for the grass cover. The boundary conditions are the flow velocity u_0 and layer thickness h_0 on the dike crest generated using the overtopping volume V. The results presented in this study are often shown as function of the overtopping volume, but the results can be transferred to a function of the flow velocity using the Equation 15 in the Appendix A, where more information on the boundary conditions and the mesh are provided.

The model calculates the water fraction α_w [-], flow velocity u [m/s], pressure p [kPa], shear stress τ_s [kN/m^2] parallel to the dike profile and the normal stress τ_n [kN/m^2] perpendicular to the dike profile as function of time and location. The water fraction is 0 for air, 1 for water and between 0 and 1 for air-water mixtures. The flow velocity, pressure, shear stress and normal stress are multiplied by the water fraction so these variables only describe the flow of water. The flow velocity is determined with a spacing of 0.5 m along the dike profile, while the other output variables are determined with a spacing of 1 cm for every boundary cell along the dike profile.

3 Wave impact on the landward slope

Firstly, numerical simulations are performed to model the wave impact process where the wave separates from the dike profile at the crest line and reattaches on the upper slope (Figure 3). The aim is to identity for which conditions flow separation occurs and how these conditions affect the location of wave impact along the landwards slope. The location of reattachment depends on the overtopping volume and slope steepness (Van Bergeijk et al., 2021b). Wave impact was observed during two wave overtopping experiments on dikes with steep slopes of 1:1.9 and 1:2.4 (Van Damme et al., 2016; Ponsioen et al., 2019).

The five dike profiles that are available for the wave overtopping tests in the Hedwige-Prosperpolder have a relatively gentle slope (Table 1). Van Bergeijk et al. (2021b) determined for which overtopping volumes wave impact occurs depending on the steepness of the landward slope. For all volumes above the threshold volume in Table 1 the wave separates at the crest line and leads to a high normal stress at the impact location where the wave reattaches to the slope. Profile 5 and 6 are most suitable for wave separation and impact experiments due to their steeper slopes. This is especially the case for studies on the effect of the overtopping volume on the wave impact process, since the maximum volume that can be simulated with the Wave Overtopping Simulator is 5.5 m^3/m.

The location of impact and the load on the cover are calculated for Profile 6 using the numerical model (Figure 2 and 4). The impact location X_{impact} is defined as the horizontal distance from the crest line to the location where the normal stress is maximum. The impact location increases with the overtopping volume, but the distance between the impact locations is small for the volumes in range 4.0 m^3/m to 5.0 m^3/m. This means that the erosion caused by the smaller overtopping volumes might affect the flow of the larger volumes and it might only be possible to perform these overtopping tests for a limited number of overtopping volumes.

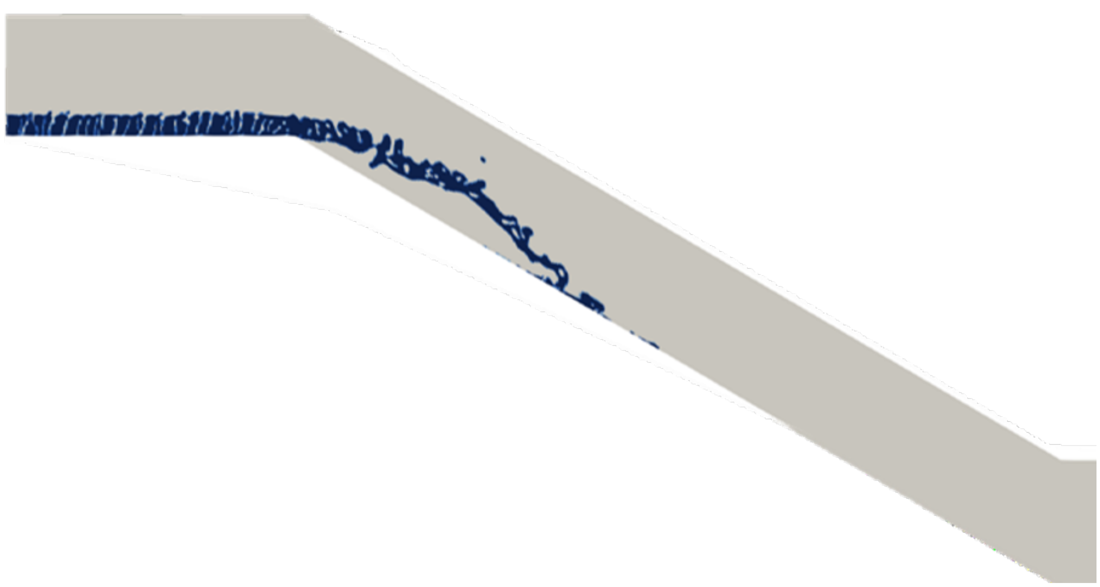

Figure 3: Snapshot of a model simulation where the wave separates at the crest line and impacts on the upper slope.

Table 1: The slope steepness of the 5 profiles for the wave overtopping experiments together with the volume threshold for wave impact.

Profile	**5**	**6**	**7**	**8**	**9**
Slope steepness	1:2.5	1:2.7	1:3.0	1:2.9	1:2.9
Threshold volume [m^3/m]	2.25	3.00	5.00	4.5	4.5

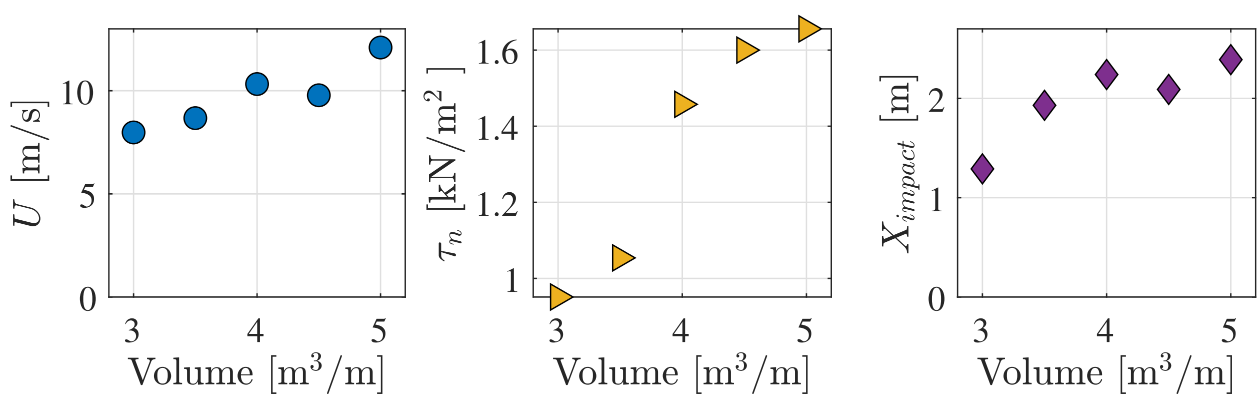

Figure 4: The maximum flow velocity U, the maximum normal stress τ_n and the location of impact X_{impact} as function of the overtopping volume for profile 6.

4 Damages

Once the dike cover is eroded, the erosion rate often increases due to a lower strength of the underlying soil layer and an increase in the hydraulic load due to wave separation and impact (Figure 1b). Model simulations are performed to determine the impact location and impact forces at this location. The model results are used to validate an analytical model that can be used to calculate the impact location, flow velocity and normal stress in an erosion model.

A damage is described by the depth d in the vertical direction and the width b in the cross-dike direction (Figure 5). The width b depends on the slope angle φ and depth as

$$b = d \tan \varphi \tag{1}$$

The flow velocity before separation u is used to calculate the impact location s_x.

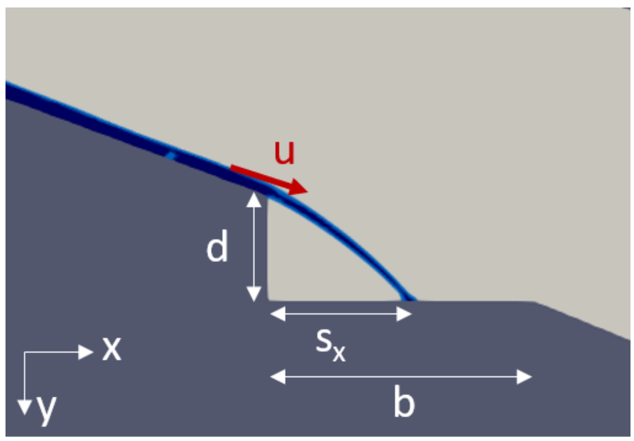

Figure 5: Snapshot of a model simulation in OpenFOAM with a volume of 1.0 m^3/m and an erosion hole with depth d of 40 cm and a length b of 1 m that lands at location s_x.

4.1 Model simulations

The simulations are performed for dike profile 6 with a crest width of 4.8 m and an average steepness of 1:2.7 (Table 2). The erosion hole is located either on the upper slope or middle slope at a horizontal distance of 3 m and 10 m from the crest line, respectively (Figure 6). The overtopping flow is simulated over the erosion holes for five overtopping volumes: 1.0 m^3/m, 2.0 m^3/m, 2.5 m^3/m, 3.0 m^3/m and 4.0 m^3/m. Four erosion holes are simulated with an erosion depth of 20 cm or 40 cm leading to 20 simulations in total.

The impact location is determined for every model simulation, where the impact location is defined as the location where the normal stress with respect to time is maximal. The maximum normal stress is also determined for every model simulation and used to derive a relation for the maximum normal stress as function of the flow velocity u and the depth d,

The model simulations are performed with a constant roughness height of 8 mm corresponding to a grass cover. A damage or erosion hole usually has a clay cover which is smoother compared to a grass cover. Van Bergeijk et al. (2020) showed that the roughness

Table 2: The location and depth of the four erosion holes together with the simulated overtopping volumes.

Run	Location	Depth [cm]	Volumes [m^3/m]
u20	Upper slope (x=7.8 m)	20	1, 2, 2.5, 3, 4
u40	Upper slope (x=7.8 m)	40	1, 2, 2.5, 3, 4
m20	Middle slope (x=14.8 m)	20	1, 2, 2.5, 3, 4
m40	Middle slope (x=14.8 m)	40	1, 2, 2.5, 3, 4

height has no significant effect on the modelled flow velocity. Since we are mainly interested in the effect of the overtopping volume and depth on the impact location and normal stress, the roughness height is kept constant.

4.2 Analytical model

The impact location s_x (Figure 5) can be calculated using the basic formulas for the trajectory of a projectile. Firstly, we set the vertical trajectory to the depth d and solve for the time t

$$u \sin(\varphi) t + \frac{1}{2} g t^2 = d \tag{2}$$

with the slope angle φ and the gravitational acceleration g. The time t is used to calculate the horizontal trajectory:

$$s_x = u \cos(\varphi) t \tag{3}$$

The magnitude of the flow velocity u at the damage can be calculated using the analytical formulas of Van Bergeijk et al. (2019). The maximum flow velocity along the dike crest u_{crest}

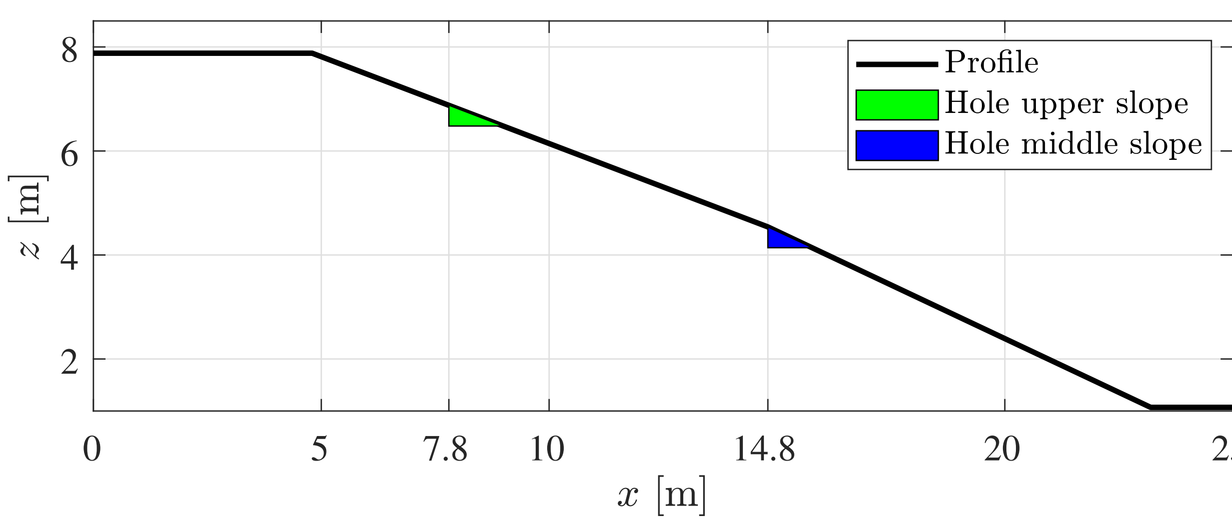

Figure 6: The location of the erosion hole on the upper slope and middle slope with a depth of 40 cm.

is calculated as

$$u_{crest}(x) = \left(\frac{fx}{2h_0u_0} + \frac{1}{u_0}\right)^{-1} \tag{4}$$

where the friction coefficient f is 0.01 for grass (SBW, 2012). The flow velocity along the slope $u_{slope}(x)$ is calculated using

$$u_{slope}(x) = \frac{\alpha}{\beta} + \mu \exp\left(-3\,\alpha\,\beta^2\,(x - B_c)/\cos(\varphi)\right) \tag{5}$$

where the parameters μ, α and β are calculated as

$$\begin{aligned} \mu &= u_{crest}(x = B_c) - \frac{\alpha}{\beta} \\ \alpha &= \sqrt[3]{g \sin\varphi} \\ \beta &= \sqrt[3]{f/2h_0u_0}. \end{aligned} \tag{6}$$

with the crest width B_c.

These analytical formulas are used to calculate the impact location s_x for the same situation as the model simulations. Firstly, the flow velocity and the layer thickness at the start of the dike crest are calculated for the overtopping volume using Equation 15. Next, the flow velocity at the end of the dike crest $u_{crest}(x = B_c)$ and the flow velocity on the slope $u_{slope}(x)$ at the location of the damage ($x = 7.8$ m or $x = 14.8$ m) is calculate using Equations 4 and 5. Finally, we can calculate the time of the trajectory (Equation 2) and the impact location s_x (Equation 3). The calculated impact location is compared to the modelled impact location to validate the analytical model.

4.3 Impact location

The impact location increases with the depth of the erosion hole and the overtopping volume. The location of the hole has minor effect on the impact location where the impact location is only slightly smaller for the upper slope compared to the middle slope as the result of a lower flow velocity. The analytical formulas describe the impact location well with a Nash-Sutcliffe efficiency factor of 0.84 (Nash and Sutcliffe, 1970). This factor quantifies the deviation from the one-to-one relationship between the model results (the analytical model in our case) and the observations (the openfoam model results in our case), where an efficiency factor of 0 means that the model predictations are as accurate as the mean of the observations and an efficiency factor of 1 indicates a perfect match.

The effect of the erosion depth is captured well in the model (indicated by the different markers) but the effect of the overtopping volume is slightly underestimated as seen for example in the spread of results for m40. This could be an indication that the analytical model needs to be improved for larger depths. The good agreement between the numerical results and the analytical formulas show that the analytical formulas can be used to derive the size of an erosion hole for the overtopping experiments. The size of the damage depends on the overtopping volume and can be calculated using the analytical model for the impact location of the wave s_x. The damage only affects the overtopping flow and the erosion process in case the wave impacts in the created damage hole. Therefore, a hole with a certain depth and width is required to speed up the erosion process. For example, the model simulations showed that the overtopping volume of 4.0 m^3/m flows completely over the damage with depth d = 20 cm and this size is therefore too small for an experiment with this specific overtopping volume.

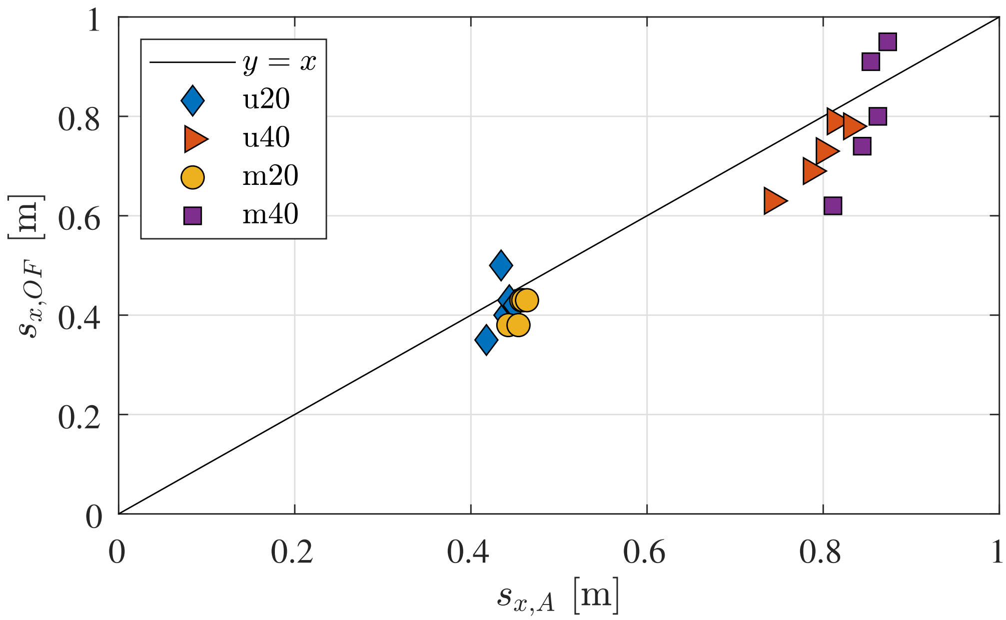

Figure 7: The impact location s_x in the numerical OpenFOAM model $s_{x,OF}$ compared to the analytical model $s_{x,A}$ where the markers indicate the model runs (Table 2) and the line indicates the one-to-one relationship.

4.4 Relation for the normal stress

The hydraulic load at the impact location is best described by the normal stress as shown by Van Bergeijk et al. (2021b) and Ponsioen et al. (2019). The analytical model calculates the flow velocity before the start of the erosion hole and we want to use this variable to express the load. The normal stress as the result of the impact also depends on the height (Stanczak, 2008; Scheres and Schüttrumpf, 2020) and therefore on the depth of the damage.

A regression analysis is performed to determine the maximum normal stress as function of the flow velocity and depth. The regression analysis showed similar results for the normal stress as function of the second and third power of the flow velocity. Since the load in the COM and GEM erosion models is both described by the flow velocity squared, the normal stress is expressed as

$$\tau_n = \max(a_1 U^2 d^{1/2} + a_2, 0) \tag{7}$$

with the factors a_1 = 0.018 $kNs^2/m^{9/2}$ and a_2 = 0.037 kN/m^2. This relationship for the normal stress can be used to express the load in head-cut and breaching models.

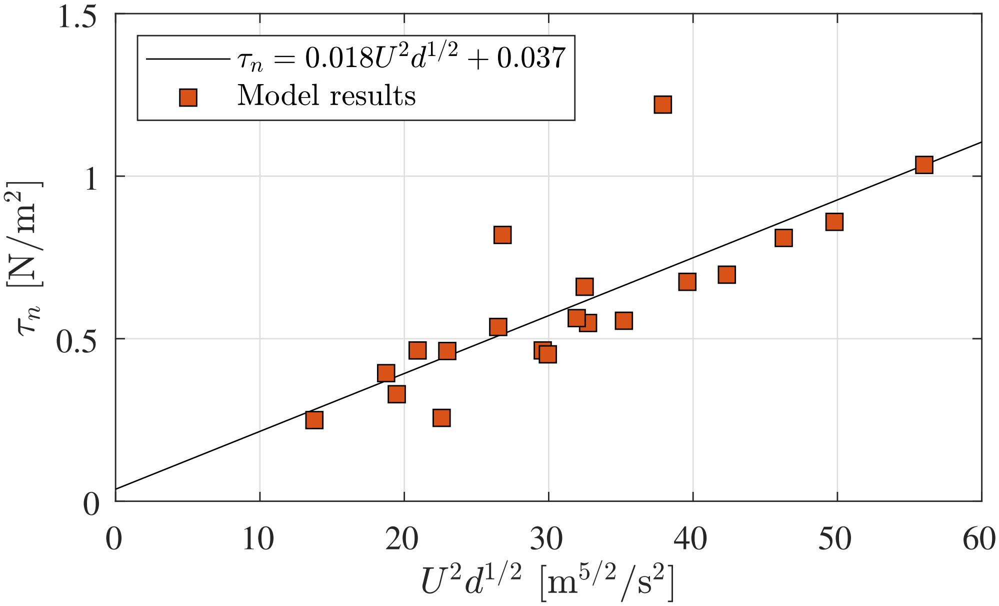

Figure 8: The maximum normal stress in the erosion hole τ_n as function of the flow velocity U and the depth d, where the line indicated the fit with a coefficient of determination of 0.62.

5 Calculation methods for erosion

Erosion by wave overtopping starts when the hydraulic load exceeds the strength of the material. This report shows how the hydraulic load as the results of wave separation and impact can be described. The hydraulic load is expressed in two hydraulic variables: the flow velocity and the normal stress. Van Bergeijk et al. (2021b) investigated the use of different hydraulic variables to describe the load by overtopping waves in erosion models and concluded that the normal stress is the only variable that describe erosion by normal forces and the flow velocity along the dike profile is the best variable to calculate the erosion by shear forces. This section describes how the formulas for the flow velocity and normal stress can be used in erosion models for cover erosion and head-cut erosion.

5.1 Cover erosion

The erosion of the cover layer is often described using models for scour erosion. These models can accurately model the erosion of the top soil of the dike cover, defined as the upper 20 cm of the dike cover where the grass roots increase the strength of the clay layer (Hoffmans, 2012).

The cumulative overload method (COM) (Van der Meer et al., 2010; Van Hoven et al., 2013) is used to describe the cover erosion by overtopping waves in the Dutch safety assessment (Van Hoven and Van der Meer, 2017). In the COM, the damage number D is calculated for every overtopping wave i and failure is defined as the exceedance of 7000 m^2/s^2,

$$D = \sum_{i}^{N} \alpha_a \alpha_m U_i^2 - \alpha_s U_c^2 \quad \text{for} \quad U_i > U_c \tag{8}$$

with the number of overtopping waves N, the flow velocity on the dike crest U_i and the critical flow velocity U_c. The acceleration factor α_a is used to calculate the acceleration along the landward slope, the load factor α_m described the increase in load at transitions and the strength factor α_s describes the decrease in cover strength at transitions. The critical flow velocity U_c describes the cover strength and depends on the quality of the grass cover.

The analytical grass-erosion model (GEM) (Van Bergeijk et al., 2021a; Warmink et al., 2020) calculates the erosion depth $d_e(x)$ along the dike profile

$$d_e(x) = \sum_{i}^{N} \left(\omega^2(x) u_i^2(x) - U_t^2(x)\right) T_0 C_E \quad \text{for} \quad \omega(x) u_i > U_t \tag{9}$$

with the turbulence parameter ω, the threshold velocity U_t, the overtopping period T_0 and the inverse strength parameter C_E. The flow velocity along the dike profile $u_i(x)$ is calculated using Equation 4 and 5. The turbulence parameter and threshold velocity depend on the cross-dike location so the reduction in cover strength and increase in load at transitions can be modelled (Van Bergeijk et al., 2021a).

The threshold velocity in the GEM is related to the critical velocity in the COM model as (Frankena, 2019; Warmink et al., 2020)

$$U_t \approx 2.4 U_c \tag{10}$$

The critical flow velocity U_c is the erosion threshold and indicates when erosion occurs. The erosion rate C_E determines the amount of erosion and translates the load to an erosion depth.

The erosion threshold and erosion rate can be determined using the erosion progression during the overtopping tests. The erosion rate can be determined by the erosion progression over time, for example the deepening of the erosion hole over time. The amount of erosion for different overtopping volumes can be used to calibrate the erosion threshold in the erosion models. The erosion rate is a soil property and is therefore independent of the overtopping volume. An increase in the amount of erosion for larger overtopping volumes is caused by an increase in the load, and can be used to calibrate the erosion threshold.

The effect of an erosion hole on the load and cover strength can be included in the COM using the load factor and strength factor and in the GEM using a local increase in the turbulence parameter and a local decrease in the threshold velocity. For example, the relation for the normal stress (Equation 7) can be transferred to

$$\alpha_m = \omega^2 = 0.32 d^{1/2} \tag{11}$$

5.2 Head-cut erosion

Once a cliff forms at an erosion hole, this cliff can migrate towards the dike crest and becomes the dominant erosion mechanism. Cliff erosion and migration can be calculated using the head-cut model (Natural Resources Conservation Service, 1997; Van Hoven, 2014), where the head-cut advance is calculated as

$$\frac{dX}{dt} = C(A - A_0) \tag{12}$$

with C the advance rate coefficient [$s^{-2/3}$] and the threshold parameter A_0 [$ms^{-1/3}$]. The load A in $ms^{-1/3}$ depends on the specific discharge q [m^2/s] and the head cut height H [m], which equals the erosion depth d in case of an erosion hole.

$$A = (qH)^{1/3} \tag{13}$$

The specific discharge remains approximately constant along the dike profile and is calculated using the flow velocity and layer thickness on the dike crest

$$q = u_0 \, h_0 \tag{14}$$

Van Hoven (2014) calibrated the threshold parameter and advance rate coefficient based on one overtopping and one overflow experiments in the Netherlands and recommends the values $A_0 = 0.1$ [$ms^{-1/3}$ and $C = 1.5 \cdot 10^{-3}$ $s^{-2/3}$. The head-cut model can be used to calculate the erosion progression once cliff migration is observed. The calibration results of Van Hoven (2014) showed a significant spread and the values for the threshold parameter and advance rate coefficient are still uncertain.

In the head-cut model, the load is independent of the location of the erosion hole, since the overtopping discharge does not change along the dike profile. Currently, only the flow velocity on the crest is used to calculate the load. The derived relation for the normal stress (Equation 7) could be used to improve the load description in the head-cut model, but this approach should first be tested using the results of wave overtopping tests.

6 Overtopping experiments

Based on the model simulations, we expect that erosion at the landward toe dominates over the erosion on the upper slope due to wave impact. Although wave impact will probably not be the dominant erosion mechanism during the overtopping experiments due to the relative small landward slope angles, we can still gather information on the hydraulic processes. The erosion at the landward toe is caused by high flow velocities and turbulence as the result of the slope change. All overtopping volumes predict erosion at the landward toe and therefore it will be hard to determine the erosive effects of different overtopping volumes. To solve this problem, we can create a damage to the grass cover at a location on the slope to speed up the erosion process at this location.

In this section, we discuss two recommended overtopping experimental designs: wave impact experiments and erosion hole experiments. Additionally, the measurements of variables are discussed that are essential to increase the knowledge on the erosion process and reduce the uncertainty in model parameters.

6.1 Wave impact

We recommend the following design for the wave impact experiments (Table 3):

I. Perform hydraulic measurements for four overtopping volumes of 2.0, 3.0, 4.0 and 5.0 m^3/m: Release each volume three times and observe if flow separation occurs. In case of wave separation, measure the impact location. Additionally, measure the flow velocity and layer thickness for all released overtopping volumes around 0.5 m in front and 0.5 m after the landward toe.

II. Erosion experiments: Release overtopping waves with a volume of 3.0 m^3/m until the cover starts to erode. Measure the location and the size of the damage. Repeat the same experiments with an overtopping volume of 5.0 m^3/m and measure the location and size of the damage.

The first experiment will provide measurements related to the location of reattachment and the threshold for wave separation. The overtopping volumes are suggested based on the model results presented in Table 1 and Figure 4. Firstly, we can test if wave does not separate for a volume of 2.0 m^3/m. The larger volumes will impact at 1.1, 2.1 and 2.44 from the crest line for 3.0, 4.0 and 5.0 m^3/m, where the difference in impact location is probably large enough to observe three individual erosion locations. Transparent screens can be placed at the upper slope around $0 - 3$ m from the crest line to observe if the waves separate and measure the landing location. The transparent screens need to be used in combination with a video camera because the process occurs in less than one second.

The second experiment can show if the location of reattachment is indeed the location where the load is maximum. The location of erosion can be measured by hand using an accuracy of around 5 cm in depth and 10 cm in the along dike and cross dike direction. The observed erosion patterns are useful to validate analytical and numerical models for the wave impact process.

No measurements of the flow velocity and layer thickness are yet available for the landward toe, while this is often the location where most erosion is observed. During the wave

Table 3: Summary of the recommended overtopping experiments.

Experiments	V [m^3/m]	Measurements
Wave impact	$2, 3, 4, 5$	Impact location using transparent screens and cameras
		Flow velocity 0.5-1 m in front and 0.5 m after the toe
		Layer thickness 0.5-1 m in front and 0.5 m after the toe
Erosion hole of 20 cm	$0.5 - 3$	Deepening of the erosion hole
		Flow velocity 1 m in front and 1m after the hole
		Layer thickness 1 m in front and 1 after the hole

impact experiments, measurements of the flow velocity at the landward toe can be performed to gain more information on the flow process at the landward toe. The layer thickness can be measured using a surfboard and the flow velocity can be measured with a paddle wheel. This paddle wheel can be mounted on the surf board to measure the flow velocity in the upper layer of the wave, or mounted on the dike surface to measure the flow velocity near the dike surface. We propose to measure the flow velocity and layer thickness around 0.5 m in front of 0.5 m after the landward toe, since most of the variation in the flow velocity occurs within this range. In case this spacing is not possible due to the required distance between the surfboards, the location can be extended to 1 m in front of and 1 m after the landward toe. Another possibility is to measure the layer thickness only in front of the landward toe, and only measure the flow velocity neat the dike surface after the landward toe using a paddle wheel mounted on the surface.

6.2 Erosion holes

Damages to the the grass cover can be created to speed up the erosion process at this location and gain insights in the cliff erosion process. The erosive effects of the different overtopping volumes can be determined by creating damages subsequently at several locations on the slope, starting from the toe toward the crest. In this study, we define an erosion hole as a hole with a vertical cliff as indicate in Figures 5 and 6.

We recommend the following design for the experiment with erosion holes (Table 3):

- Perform experiments with an erosion hole of 20 cm. This depth is chosen since the overtopping waves do not impact in the erosion hole for smaller depths (Table 4) and the thickness of the clay layer is limited so a small depth of the hole is preferred.

- Start with an erosion hole on the lower slope around 1 m from the toe. Release around 100 waves with an overtopping volume of 0.5 m^3/m and measure the deepening of the erosion hole. In case the clay layer is completely eroded, strengthen and protect the erosion hole. For the next experiment, make an erosion hole around 1-2 m towards the crest and repeat the experiment with a 100 waves of 1.0 m^3/m. Otherwise, perform the experiments with 100 waves of 1.0 m^3/m on the first erosion hole.

- This experiment can be repeated with increasing overtopping volumes in steps of 0.5 m^3/m and creating new erosion holes around 1-2 m towards the crest. The recommended range of overtopping volumes is $0.5 - 3.0$ m^3/m since the model results show that larger overtopping volumes will land landward of the erosion hole (Table 4).

- Measure the following erosion characteristics:
  - Deepening of the erosion hole with an accuracy of 5 cm in depth and 10 cm in the cross-dike and along dike direction.
  - Migration of the vertical cliff at the start of the erosion hole with an accuracy of $5 - 10$ cm.
  - In case of erosion on the slope outside of the erosion holes: measure the depth with an accuracy of 5 cm and the size with an accuracy of 20 cm x20 cm.
- The following hydraulic measurements are recommended:
  - Measurements of the flow velocity near the erosion hole around 2 m before the erosion hole and 1 m after the erosion hole. The measurement location in front of the erosion hole needs to be safe regarding the cliff migration.
  - Measurements of the flow velocity and layer thickness at the landward toe similar to the wave impact experiments.

Additionally, the modelled shear stress in the erosion holes varied between 0.23 kN/m^2 for an erosion hole of 20 cm and $V = 1.0$ m^3/m and 1.47 kN/m^2 for an erosion hole of 40 cm and $V = 4.0$ m^3/m. These values can be used as an indication for small scale tests to determine the strength of the grass cover.

Table 4: The maximum overtopping volume V that impacts in the erosion hole at location s_x for an erosion hole with depth d and width b. The waves need to impact in the erosion hole to speed up the erosion process, therefore the maximum impact location is defined as the width minus 5 cm. The landing location s_x is calculated using the analytical model for volumes in the range $0.5 - 5.5$ m^3/m and used to determine the maximum volume with a landing location smaller than the maximum s_x.

Steepness	**Depth d [m]**	**Width b [m]**	**Maximum s_x [m]**	**Maximum V [m^3/m]**
1:2.5	0.1	0.25	0.20	-
1:2.5	0.2	0.50	0.45	4
1:2.5	0.3	0.75	0.70	5.5
1:2.7	0.1	0.27	0.22	-
1:2.7	0.2	0.54	0.49	5.5
1:2.7	0.3	0.81	0.76	5.5
1:3	0.1	0.30	0.25	-
1:3	0.2	0.60	0.55	5.5
1:3	0.3	0.90	0.85	5.5

7 Conclusions

Numerical simulations were performed to design the overtopping experiments in the HedwigeProsperPolder as part of the Polder2C's project. The numerical model of Van Bergeijk et al. (2020) in OpenFOAM was used to simulate the overtopping flow and calculate the overtopping load on the dike cover. This section provides the conclusions for four objectives identified in the introduction.

Firstly, the conditions for the wave impact process were determined. It was found that only for large overtopping volumes the waves will separate at the crest line and impact on the upper slope. Therefore, wave impact will probably not be the dominant failure mechanisms during the wave overtopping experiments. The modelled location of reattachment varies between 1.1 m from the crest line for $V = 3.0$ m^3/m and 2.44 m for $V = 5.0$ m^3/m.

Secondly, an analytical model was developed to calculate the impact location of the overtopping wave in an erosion hole based on the overtopping flow velocity. A relation between the maximum normal stress as function of the flow velocity was determined using the numerical model results. This relation can be used to describe the load in an erosion hole for head-cut and breaching models.

Thirdly, an overview of the existing calculation methods for erosion identified the erosion parameters that are useful to determine during the overtopping experiments. For cover erosion models, the erosion threshold and erosion rate need to be measured. Additionally, measurements of the deepening and progression of the erosion holes are proposed to increase the understanding of the head-cut erosion process and reduce the uncertainty in the model parameters in the head-cut model.

Finally, a preliminary design of the overtopping experiments is provided. Wave impact experiments are performed to measure the location of reattachment and the threshold for wave separation. Additionally, erosion holes can be created on the landward slope to speed up the erosion process. Multiple overtopping experiments with a 20 cm deep erosion hole and increasing volumes can be performed subsequently on one dike section to gather as much information as possible to determine the erosion rate and erosion threshold of the cover. Measurements of the layer thickness and flow velocity at transitions such as the landward toe and around erosion holes are necessary to validate the hydraulic load in analytical and numerical models.

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List of Symbols

A	load in heat-cut model	[m/s$^{1/3}$]
A_0	threshold parameter	[m/s$^{1/3}$]
b	width of the damage	[m]
B_c	crest width	[m]
C	advance rate coefficient	[s$^{-2/3}$]
C_E	inverse strength parameter	[s/m]
d	depth of the damage	[m]
d_e	erosion depth	[m]
D	damage number	[m^2/s^2]
f	friction coefficient	[-]
g	gravitational acceleration	[m/s^2]
h_0	layer thickness at the start of the dike crest	[m/s]
H	Head-cut height	[m]
N	number of waves	[-]
p	pressure	[kPa]
q	overtopping discharge	[m^2/s]
s_x	impact location	[m]
t	time	[s]
T_0	overtopping period	[s]
u	flow velocity	[m/s]
u_0	flow velocity at the start of the dike crest	[m/s]
u_{crest}	flow velocity along the dike crest	[m/s]
u_{slope}	flow velocity along the dike slope	[m/s]
U	maximum flow velocity with respect to time	[m/s]
U_c	critical velocity	[m/s]
U_t	threshold velocity	[m/s]
V	overtopping volume	[m^3/m]
x	cross-dike coordinate	[m]
X_{impact}	impact location	[m]
α_a	acceleration factor	[-]
α_m	load factor	[-]
α_s	strength factor	[-]
α_w	water fraction	[-]
τ_s	shear stress parallel to the dike profile	[kN/m^2]
τ_n	normal stress perpendicular to the dike profile	[kN/m^2]
φ	landward slope angle	[°]
ω	turbulence parameter	[-]

A Details of the numerical OpenFOAM model

This appendix describes the generation of the boundary conditions and mesh in the OpenFOAM model in more detail. The OpenFOAM code of the model simulation of an overtopping wave with a volume of 5500 l/m is shared with the partners in the Polders2C's project. The validation of the numerical model and more information on the output of the model are described in the following papers:

- Van Bergeijk, V.M., Warmink, J.J. Hulscher, S.J.M.H. (2020). Modelling the Wave Overtopping Flow over the Crest and the Landward Slope of Grass-Covered Flood Defences. Journal of Marine Science and Engineering, 8, 489. Freely available at: https://doi.org/10.3390/jmse8070489
- Van Bergeijk, V.M., Warmink, J.J. Hulscher, S.J.M.H. (-). The wave overtopping load on landward slopes of grass-covered flood defences: deriving practical formulations using a numerical model. Submitted. Paper can be shared on request.

Matlab codes for the generation of the boundary conditions and post processing of the model output can be shared on request. The model used for the simulations with the erosion holes is still under development. Feel free to contact the researchers at the University of Twente with any questions related to the OpenFOAM model. We are open for collaboration to further improve and develop the overtopping models.

A.1 Boundary conditions

The boundary conditions are the maximum flow velocity u_0 and maximum layer thickness h_0 on the dike crest generated using empirical relations and the overtopping volume V (Van der Meer et al., 2010; Hughes and Shaw, 2011)

$$u_0 = 4.5\, V^{0.34} \quad \text{and} \quad h_0 = 0.133\; V^{0.5}. \tag{15}$$

Following Hughes (2011), an idealised saw-tooth shape is used to describe the layer thickness h and flow velocity u as a function of the time t (Figure 9).

$$h(t) = h_0 \left[1 - \frac{t}{T_0}\right] \qquad \text{for } 0 \le t \le T_0 \tag{16}$$

$$u(t) = u_0 \left[1 - \frac{t}{T_0}\right] \qquad \text{for } 0 \le t \le T_0 \tag{17}$$

The overtopping period T_0 is calculated using the empirical formula of Van der Meer et al. (2010) for the overtopping period on the crest.

$$T_0 = 4.4\; V^{0.3} \tag{18}$$

In OpenFOAM, the boundary conditions are generated using the *lookuptables* function of the *groovyBC* library, which is part of the *swak4Foam* library. The time series of the flow

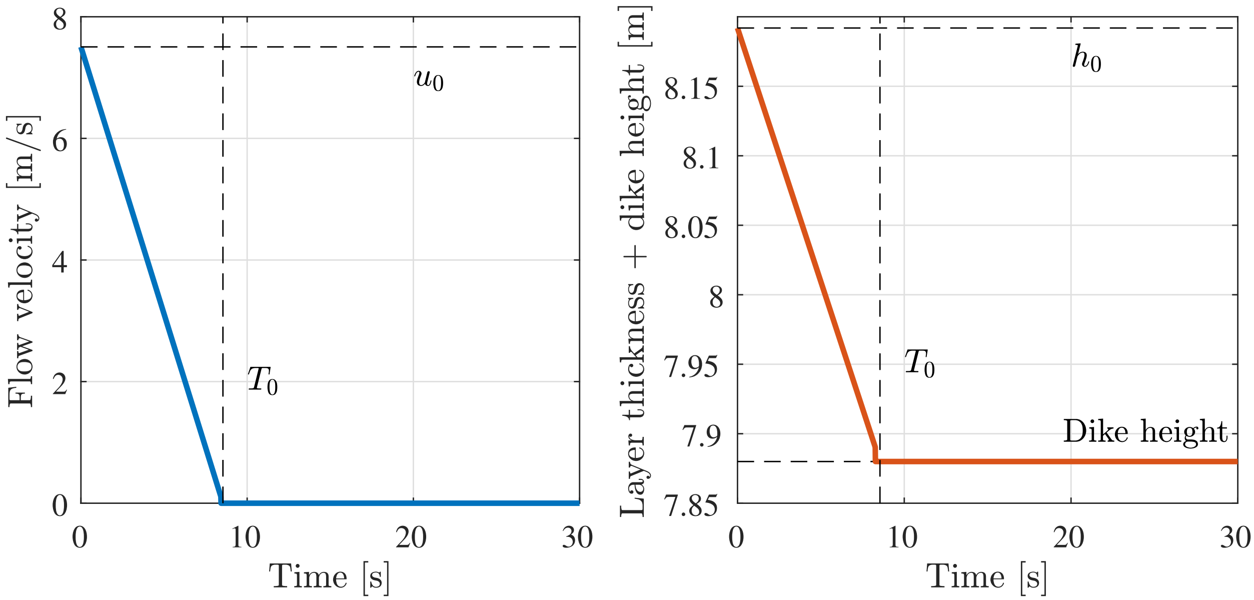

Figure 9: Boundary conditions for overtopping volume of 5.5 m^3/m showing the maximum flow velocity u_0 and maximum layer thickness h_0 at the start of the crest and the overtopping period T_0.

velocity and layer thickness at the start of the model domain (Figure 9) are generated in matlab using the empirical formulas (Equation 15 - 18) where the dike height is added to the layer thickness. The time series are generated per overtopping volume and transferred to separate texts files. In OpenFOAM, the boundary condition for the water fraction α_{water} sets the boundary cells at the start of the domain ($x = 0$ m) with a height smaller than the layer thickness plus the dike height to 0.8 (Van Bergeijk et al., 2020, 2021b). This means that the inflow of the overtopping waves consists of 80% of water and 20% of air similar to the measured air content of overtopping waves during field tests (Hoffmans, 2012). The empirical formulas for the layer thickness are based on measurements with a surfboard that measures the layer thickness including the air content and therefore the air content is also included in the boundary conditions of the model.

A.2 Mesh

The simulations in this study are performed for profile 6 (Figure 10). The measurements of the dike profile are used to generate an idealised dike profile consisting of four blocks: the dike crest ($x = 0 - 4.8$ m), the upper slope ($x = 4.8 - 14.8$ m), the lower slope ($x = 14.8 - 23.2$ m and a horizontal part after the landward toe ($x = 23.2 - 25$ m). An idealised profile is chosen since the grid is more efficient and therefore saves computational costs. Also, the results are more generally applicable and less specific for this profile. For example, the measured profile shows a small bump around 22.5 m affecting the results which is not the case for the idealised profile. Additionally, a sharp change in slope angle from the crest to the slope is necessary to simulate the wave impact process.

The idealised profile is generated in blockMesh with a vertical height of 1 m and grid sizes of 1 cm x 1 cm. The mesh of a measured dike profile can be generated using the

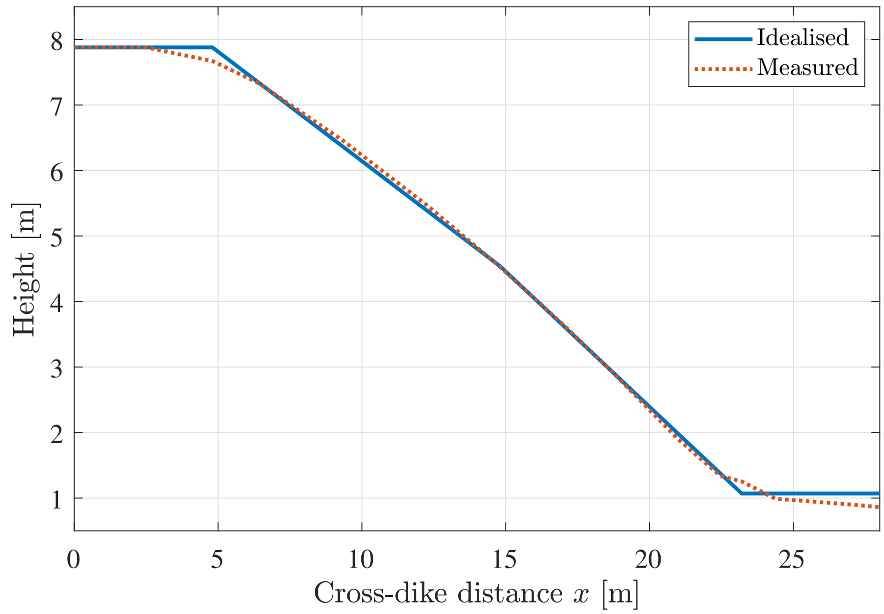

Figure 10: Dike profile 6 based on measurements and the idealised profile used in the simulations.

snappyHexMesh functions where the measurement points can be added to the STL definitions file in the constant/triSurface folder. The mesh is generated following these three steps and can be ran using the runMesh function in the model.

I. Create the background mesh using blockMesh

II. Create the boundary files of the measured dike profile: (1) the .stl file using the faceSetToSTL function which is included in the waves2foam toolbox and (2) the .emesh file using the surfaceFeatureExtract function

III. Run the snappyHexMesh function consisting of three steps: (1) removing the cells outside of the mesh defined in the stl file, (2) snapping the mesh and (3) addition of layers (OpenCFD Ltd., 2019)

The overtopping volume of 5.5 m^3/m is simulated for the measured and the idealised profile to show the differences. Firstly, the wave did not separate at the crest line for the measured profile while for the idealised profile large impact forces where modelled due to wave impact. Except from the impact location, the flow velocity is similar for both profiles while the pressure, shear stress and normal stress are small on the slope for both profiles. The landward toe is located at $x = 22.5$ m for the measured profile and at 23.3 m for the idealised profile. For both the measured profile and the idealised profile, the pressure, shear stress and normal stress increase at the landward toe. The magnitude of these three variables is larger for the idealised profile compared to the measured profile, probably because of the more abrupt change in slope. The toe does not seem to have an effect on the flow velocity for the measured profile while the flow velocity increases after the toe for the idealised profile.

The mesh of the simulations with an erosion hole are also created using a combination of blockMesh and snappyHexMesh. An additional block was generated using blockMesh to make sure that the grid cells in the erosion hole align with the other grid cells. Layers along the profile can be added parallel to the dike profile in snappyHexMesh which results in more

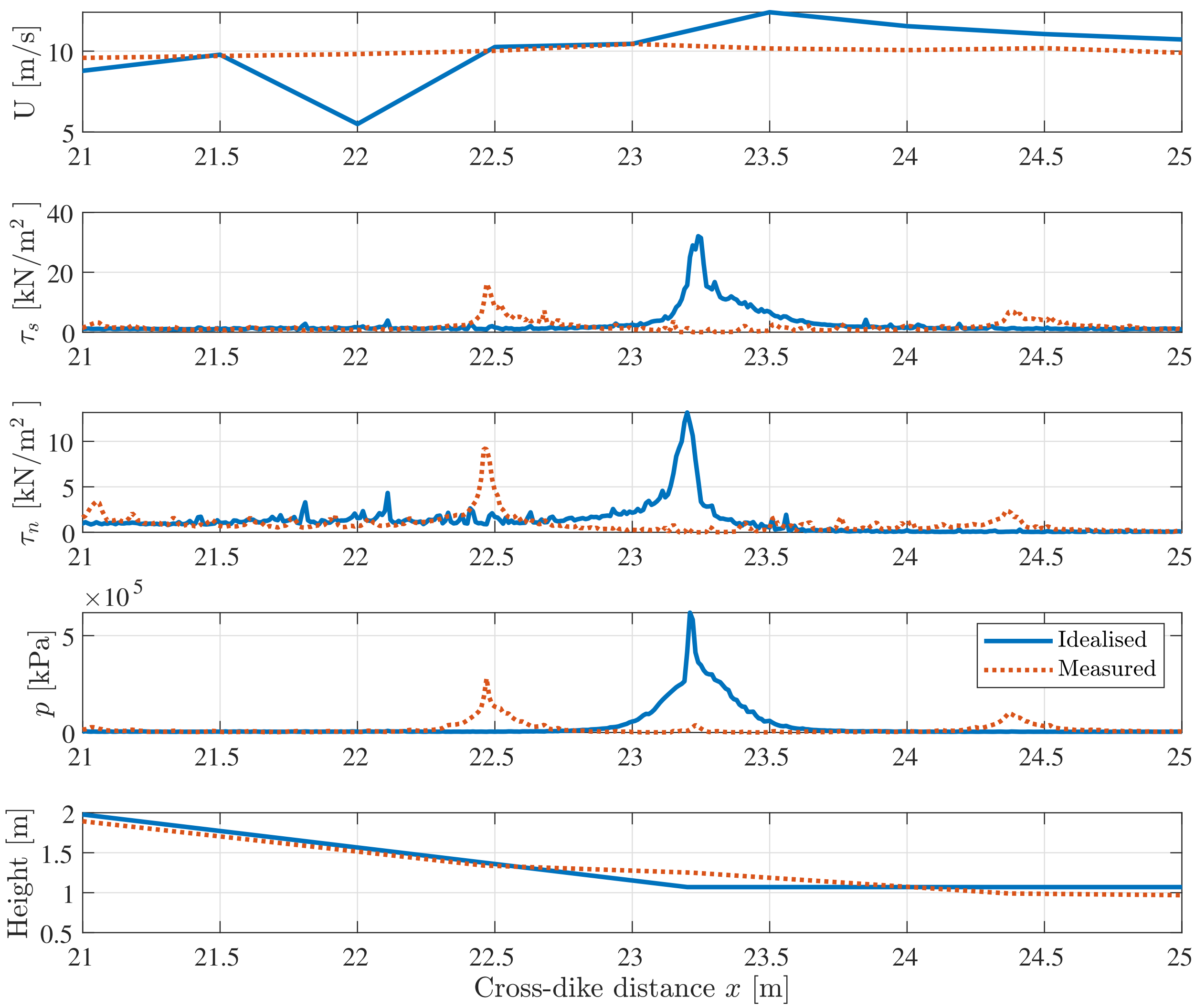

Figure 11: The hydraulic variables at the landward toe of the measured and idealised profile showing the maximum flow velocity U, the maximum shear stress τ_s, the maximum normal stress τ_n and the maximum pressure p with respect to time

hexahedron cells along the dike surface contrary to the case without layers where the cells on the dike surface have different shapes as result of the snapping process (Figure 12). However, the layer addition results in a small disturbance of the mesh further from the surface. In this section, we compare the model simulations using a grid with an erosion hole with and without layers.

Figure 13 show the shear stress, normal stress and pressure in an erosion hole for an overtopping volume of 2.5 m^3/m. The forces on the vertical wall are small compared to the horizontal part of the erosion hole. The pressure is similar for both cases, but the case with no layers results in additional peaks compared to the case with layers. These additional peaks can be the results of the irregular shapes of the boundary layer where the shear stress and normal stress are calculated. Therefore, we decided to perform the simulations of erosion holes including layers.

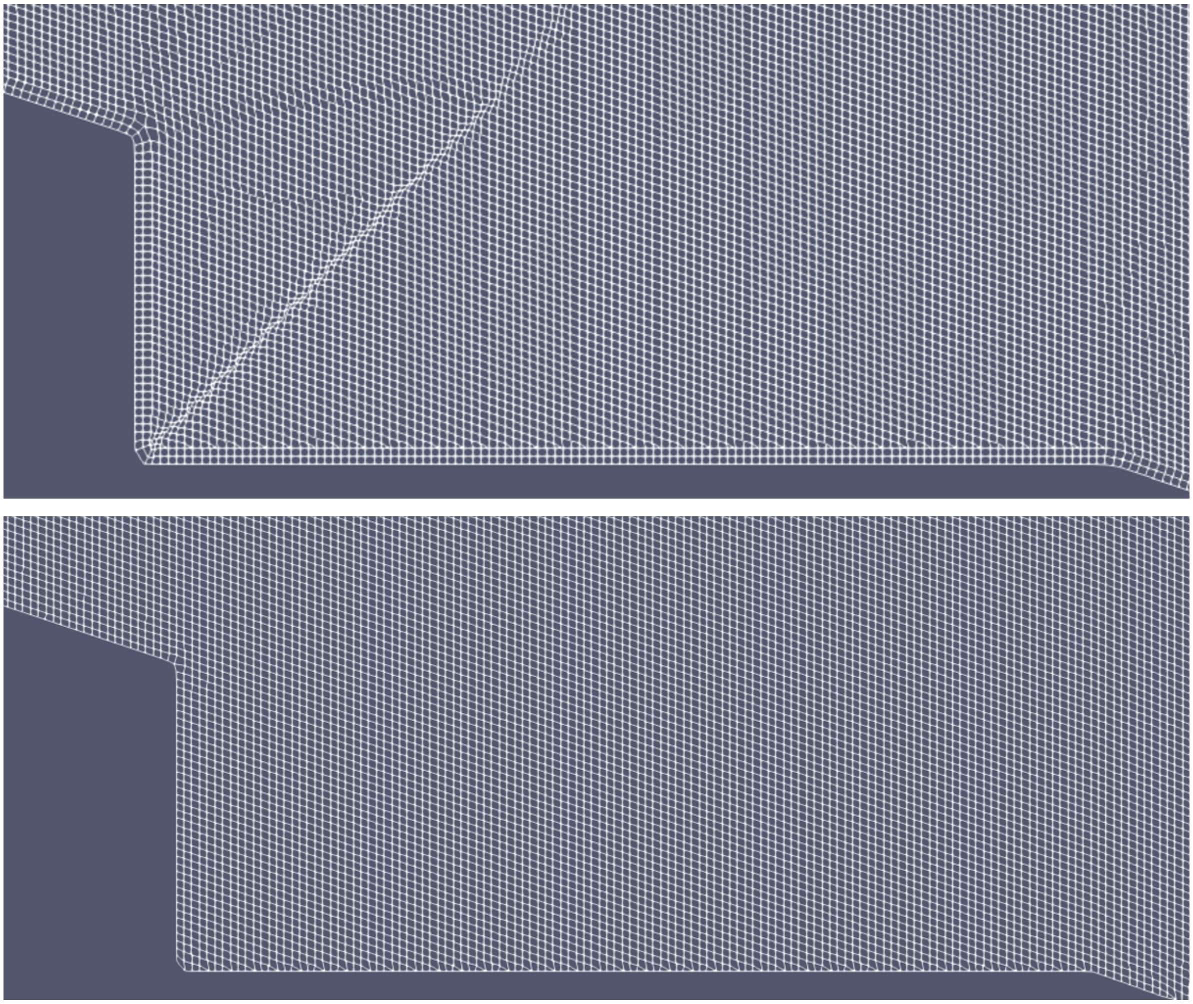

Figure 12: The grid cells in the erosion hole in the case with layers (top) and without layers (bottom).

A.3 Output

The shear stress and normal stress on the dike cover are determined using the wallShearStress function in OpenFOAM. This provides the stress in Cartesian coordinates, which are transferred to the shear stress parallel to the dike profile and the normal stress perpendicular to the dike profile using the normal vector of every boundary cell. The standard wallShearStress code in OpenFOAM was adapted to print the normal vector Sf of every boundary cell. Additionally, the coordinates of every boundary cell are required to the sort the shear stress, normal stress and pressure along the dike profile. Additionally, the shear stress and the normal stress are multiplied by the density of water to obtain the stress in N/m^2.

The pressure on the dike cover is sampled using the function samplePressureSurface. The flow velocity presented in this study is the flow velocity in the top layer of the overtopping wave and is sampled at every 0.5 m along the dike profile. During the post processing in Matlab, the flow velocity in the top layer is defined as the flow velocity in the highest cell that contains more than 60% of water.

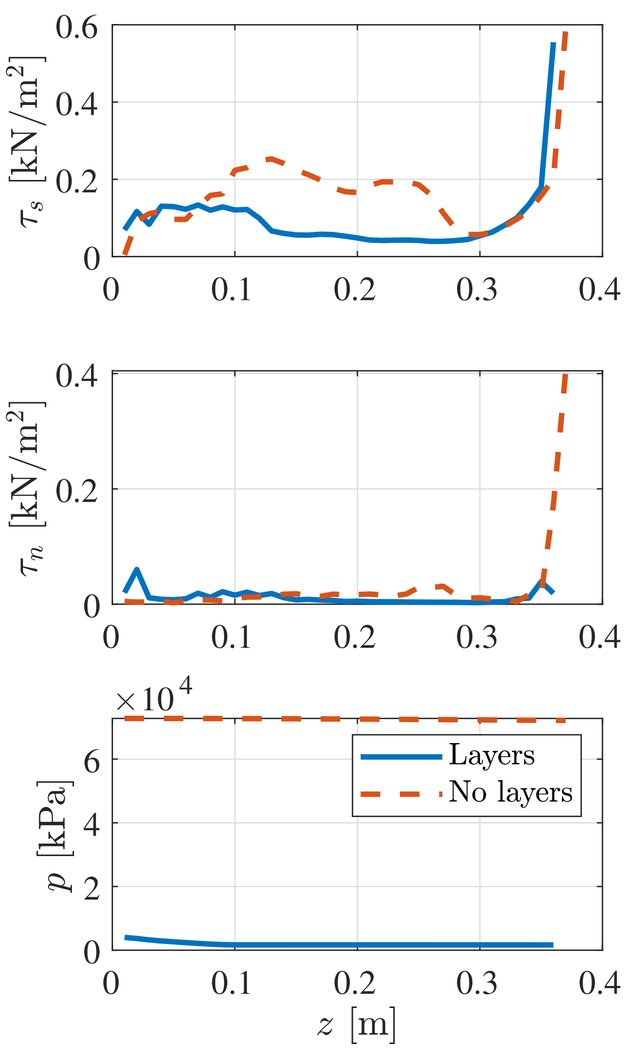

Figure 13: The forces on the dike surface of the vertical part of the erosion hole (left) and horizontal part of the erosion hole (right) showing the maximum shear stress τ_s, normal stress τ_n and the pressure p with respect to time.