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Erosion at transitions in landward slopes of dikes due to wave overtopping

Henk VERHEIJ[1], Gijs HOFFMANS[2], Bianca HARDEMAN[3], Maurice PAULISSEN[4],

[1] Delft University of Technology and Deltares
Rotterdamseweg 185, 2600 MH Delft, The Netherlands. Email: h.j.verheij@tudelft.nl

[2] Deltares
Rotterdamseweg 185, 2600 MH Delft, The Netherlands. Email: gijs.hoffmans@deltares.nl

[3]Rijkswaterstaat, Centre for Water Management
Zuiderwagenplein 2, 8224AD Lelystad, The Netherlands. Email: bianca.hardeman@rws.nl

[4]Alterra|Wageningen University and Research Centre
Droevendaalsesteeg 3, 6708PB Wageningen, The Netherlands. Email: maurice.paulissen@wur.nl

Destructive wave overtopping tests have been performed at more than 20 dike sections in the Netherlands using the Wave Overtopping Simulator to simulate the overtopping waves. The tests show the combined behaviour of turf and substrate up to mean wave overtopping discharges of 75 ℓ/s per m, meaning wave volumes up to 5,500 ℓ/m with flow velocities up to 8 m/s. Observed failure mechanisms are (1) erosion of the grass cover on the slope, (2) erosion at transitions to a horizontal berm or at the toe, and (3) erosion related to non-water retaining structures such as a concrete staircase in the slope, fences, and poles.

Based on observations during the tests, preliminary conclusions are that transitions from slope to horizontal dike sections are the most vulnerable locations for damage. The dike slope itself covered with grass on clay never failed by erosion due to a mean overtopping discharge of 10 ℓ/s per m or less. Obviously, non-water retaining structures such as a staircase in the slope induces significant scour holes due to the concentrated flow adjacent of the staircase.

The paper deals with the failure mechanism erosion at transitions. The overtopping wave acts as a jet impacting on the horizontal section and creates a scour hole. The scour hole increases during each overtopping wave with a certain "amount of energy" above a threshold value determined by the characteristics of the grass-clay cover. Model development is going on based on both the analogy with jet erosion and the method according to the excess of the shear stress. Additional tests will be carried out from 2012 on sea and river dikes to further develop the erosion models.

Key words
dikes, levees, erosion, grass, overtopping, waves, transitions.

I INTRODUCTION

Since 2007, destructive wave overtopping tests are conducted on real dikes in the Netherlands as part of the Strength and Loads on Water Defences Programme. The test are commissioned by the Ministry of Transport, Public Works and Water Management (Rijkswaterstaat, Centre for Water Management). However, not only tests have been carried out in the Netherlands, but also in Belgium and Vietnam. The aim of the wave overtopping tests is to better understand the role of grass-covered inner slopes with respect to dike strength. Based on tests with a wave overtopping simulator (Figure 1) the following damage mechanisms are distinguished:

1. Erosion of the grass cover on the slope;
2. Erosion at transitions from slope to a horizontal berm or at the toe;
3. Erosion related to non-water retaining structures such as a concrete staircase in the slope, fences, trees and poles.

After the initial failure mechanisms further erosion might be initiated:

- Gradual eroding of the grass cover in downstream direction (development of gullies);
- Enlargement of the scour hole in upstream direction (head-cut erosion).

Figure 1 Test setup

The paper deals with the failure mechanism "erosion at transitions" as shown in Figure 2. The experiences regarding the other failure mechanisms are discussed in Section II.

Figure 2 Extensive damage at maintenance road at the transition slope to horizontal at the toe with progressive head-cut erosion

Transitions to the horizontal can be found at the toe of a dike, but also halfway the slope, see the sketch with a grassed berm in Figure 3. They are an abrupt change in the slope. The overtopping wave coming down the slope acts as a jet impacting on the horizontal section, subsequently, initiating erosion and resulting finally in a scour hole if the strength of the grass cover or pavement is insufficient. This process can be modelled by either the jet theory, or the approach of the effective cumulative load as developed for the straight slope. Both approaches are discussed in Section III.

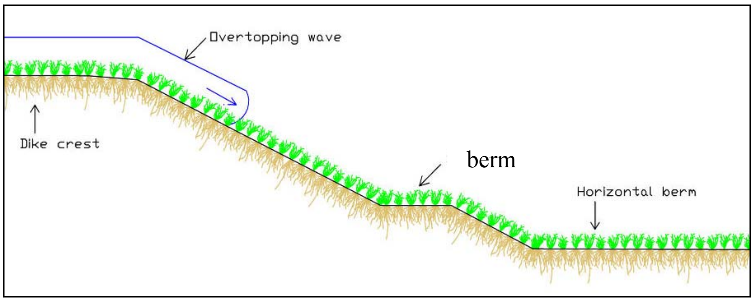

Figure 3 Transitions at an inner dike slope

II EXPERIENCES WITH THE STRENGHT OF THE INNER SLOPE

Destructive overtopping tests were carried out on real dikes at more than 20 different locations (more than 1000 m^2 grass cover) by using the Wave Overtopping Simulator to simulate the overtopping waves (Van der Meer et al. 2008 and 2009). With the wave overtopping simulator the effect of extreme conditions can be simulated. At each dike section, tested overtopping conditions were simulated of discharges of 0.1 ℓ/s per m up to 75 ℓ/s per m, each discharge lasting for 6 hours. Hence, wave volumes of 200 ℓ/m up to 5,500 ℓ/m with flow velocities up to 8 m/s may erode dikes. The significant wave height varied from 1 m to 3 m. The grass cover differed at each section in terms of turf quality (number of roots, open area), vegetation type, composition (more sandy versus clayey content), and management status.

In general, preliminary conclusions based on observations during the Dutch tests are that a straight slope covered with grass on clay never will fail by erosion due to a mean overtopping discharge of 30 ℓ/s per unit width or less. Transitions from slope to the horizontal proved to be the most vulnerable locations for damage (Figure 4). In particular, if there is a maintenance road made of bricks on a sand foundation (Figure 5). Non-water retaining structures such as a staircase in the slope also induced large scour holes due to the concentrated flow adjacent of the staircase. Then, damage started already by a mean discharge of less than 10 ℓ/s per unit width. More detailed observations are:

- Failure of the grass cover for discharges larger than 30 ℓ/s per m for a significant wave height of 2 m, but regularly even no failure for 75 ℓ/s per m.
- Transitions from slope to horizontal are more erosion sensitive than the slope, however, by making a gradual transition damage can be prevented.
- The presence of a brick pavement on a under layer of sand on a berm results in considerable larger damage than a grass cover.
- Large objects result in concentrated damage (staircase, tree).
- Small objects and small initial damage have hardly any effect.

It can also be concluded that fatigue plays a role. Not the biggest wave results in a failure, but a number of big waves. This resulted in the hypothesis of the cumulative effective hydraulic load being a measure for the damage (or erosion) level. Van der Meer et al. (2010) proposed the following damage equation:

$$D = \sum_{i=1}^{N} \left(U^2 - U_c^2 \right) \quad (1)$$

where D is the damage number, N is the number of waves for $U > U_c$, U is the maximum depth-averaged flow velocity during an overtopping event, and U_c is the critical depth-averaged flow velocity. The damage number is determined by the number of waves, the flow velocity of the largest wave volumes and observations after the hydraulic measurements.

The flow velocity U and water depth h of the overtopping wave can be determined with empirical relationships based on overtopping tests (Van der Meer et al, 2010):

$$U = 5.0V^{0.34} \quad (2)$$

$$h = 0.133V^{0.5} \quad (3)$$

where V is the volume of the overtopping wave which can be computed with (EurOtop Manual, 2007):

$$P_v = 1 - \exp\left[-\left(\frac{V}{a} \right)^{0.75} \right] \text{ and } a = 0.84 T_m q N_w / N_{ow} \quad (4)$$

where P_v = probability of the overtopping volume V, T_m is the mean wave period, q is the overtopping discharge, N_w is the number of incident waves, and N_{wo} is the number of overtopping waves. For a given significant wave height and wave period and overtopping discharge the wave volumes can be computed. These biggest volumes are up to 6,000 ℓ per m with flow velocities of about 9 m/s and water depths of 0.3m.

A grass cover prevents erosion and is an effective control measure. This form of protection has long been used for agricultural drainage channels and on slopes of dikes. For grass covers relatively large forces are required to break up these aggregates within the ground level. Nevertheless, erosion of a grass cover on a slope is possible and starts with the development of a scour hole at a weak spot where the roots are ripped off by the pressure differences induced by the overflowing water. The initial scour hole increases during each overtopping wave of which a certain 'amount of energy' is above a threshold value. This was confirmed by the overtopping tests as initiation of damage and ongoing damage was observed for mean overtopping discharges of at least 50 ℓ/s per unit width. Then, the amount of energy was sufficiently high.

The overall strength of a dike body depends on its weakest link. As said before, transitions in a profile are the weak spots in the dike system. The results of the wave overtopping experiments supported the idea that profile changes in a dike profile, e.g. at the toe of the inner slope, which is very often also used as a maintenance road, are the weak spots. Figure 4 shows the damage of a berm with an open block pavement. Figure 5 shows the scour development at a toe with a hidden brick path under a grass top layer.

Figure 4 Damaged open concrete block pavement on a berm (left: removed blocks on the downstream slope; right: initial scour hole development at the upstream side of the pavement)

Figure 5 Scour hole development at the toe with a hidden brick path (left: overview; right: detail)

III MODEL DEVELOPMENT

Two approaches are described, namely a more theoretical one based on jet scour allowing the prediction of the equilibrium depth and the time development of a scour hole and a more practical approach by using the cumulative effective hydraulic load as developed for a straight slope.

III.1 Cumulative effective hydraulic load

The cumulative effective hydraulic load is based on the excess of the shear stress, and in principle identical to the hydraulic work approach, as mentioned by Dean et al (2010). Eq. 1 describes the criterion in which the first term is a measure for the erosion and the second one a measure for the fatigue. Based on all tests the result is:

- First damage (evolving superficial erosion spots or single damaged spot);
- Various damaged locations;
- Failure (ongoing damage reaching the core of the dike).

Essential are the flow velocity in the overtopping wave and a critical velocity, which should be exceeded before erosion will take place. Depending on the test section the critical flow velocity varied between 4 m/s for a sandy dike to at least 6 m/s for a clay dike. Failure of the dike occurs if the sand core underneath the grass cover erodes fast. Usually the “initial damage” is identified with a first small erosion hole. However, this criterion is not unambiguous as it depends on the existence of one weak spot only. A more reliable criterion can be given if more weak spots are considered, such as "damage at various locations". Besides these erosion criteria there is also a need for the condition "failure of dike slope". This resulted in the following criteria:

first damage $D < 500\ \mathrm{m^2/s^2}$ (5)

damage at various locations $500\ \mathrm{m^2/s^2} < D < 1500\ \mathrm{m^2/s^2}$ (6)

failure of dike slope $D > 3500\ \mathrm{m^2/s^2}$ (7)

The overload method as presented in Eq.1 is modified for a transition from slope to horizontal into:

$$D = \sum_{i=1}^{N}\left(\left(\alpha_m U\right)^2 - U_c^2\right) \tag{8}$$

where α_m is a multiplyer to take into account the heavier hydraulic load at the transition. The value of α_m is assumed to be in the range of 1.0 to 2.0 on the basis of theoretical considerations.

Knowing the overtopping volumes and the flow velocities per overtopping wave volume, it is possible to calculate the cumulative hydraulic load. However, the effective load also depends on the critical flow velocity. The main question is now what is the critical flow velocity? It is known that grass can easily resist flow velocities of up to 2.0 m/s. Higher velocities can also be withstood. However, the critical value depends strongly on the root qualities and the changes of the suction pressures. The mean grass strength is a function of the root area ratio, the mean root diameter and the critical mean root tensile stress.

Assuming that the flow is hydraulically rough and for the condition of incipient motion $U = U_c$, the critical depth-averaged velocity for grass reads (Hoffmans, 2012)

$$U_c = \alpha_{grass,U} r_0^{-1} \sqrt{\Psi_c \sigma_{grass,c}(0)/\rho} \quad \text{with} \quad \alpha_{grass,U} = 2.0 \tag{9}$$

where r_0 is the relative turbulence intensity, Ψ_c is the critical Shields parameter, $\sigma_{grass,c}(0)$ is the critical grass strength at the soil surface, and ρ is the density of water.

III.2 Scour depth based on analogy with jet erosion

Different researchers developed formulas for predicting scour by jets, for example Hoffmans (2012), Stein et al. (1993) and Valk (2009). Here, the Hoffmans approach is presented, see Figure 6 for definitions. The equation reads:

$$z_{m,e} + h_t = c_{2v}\sqrt{\frac{qU\sin\theta}{g}} \quad \text{with} \quad c_{2v} = \frac{23}{\left(U_c\left(\Delta/(\nu g)\right)^{1/3}\right)^{1/2}} \tag{10}$$

where c_{2v} is the characteristic non-dimensional parameter for the soil strength (-); g is the gravitational constant (m/s^2); h_t is the downstream water depth on the horizontal (m); q is the instantaneous overtopping discharge (m^3/s/m); θ is the inner slope gradient (-); $z_{m,e}$ is the maximum equilibrium scour depth (m); Δ is the relative density (-); ν is the kinematic viscosity (m^2/s).

Hoffmans derived the equation on the basis of the second law of Newton and modified the original equation for non-cohesive materials and the increased strength due to the presence of roots. It is assumed that the maximum scour depth will be reached during a simulated storm of 6 hours which is reasonable since most of the scouring occurs in the initial stages.

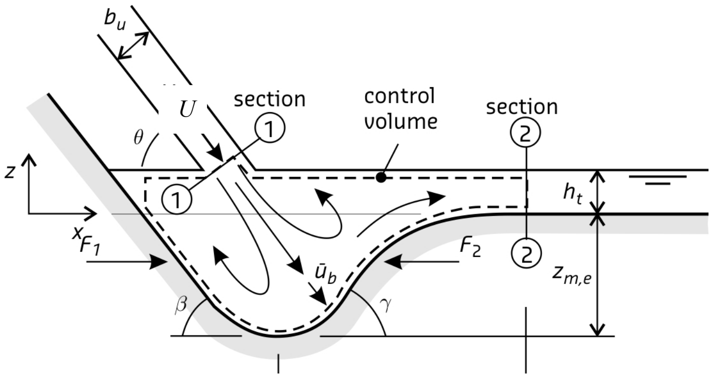

Figure 6 Definition sketch oblique plunging jet

The overtopping discharge q can be determined with $q = hU$ with h is the thickness of the water layer on the slope (note that in Figure 6 the water layer thickness is given as b_u). The value of 23 in the equation for the dimensionless strength is the result of a validation using a limited number of test results with scour depth of 0.4 m to 1.0 m. Substituting known values for the different parameters allows the calculation of the scour depth.

It should be noted that if the transition is very gradual no erosion will occur at the toe. This was also observed at one of the test sections.

The disadvantage of Eq.10 is that it does not predict time dependent scour.

As mentioned before, also Stein et al. (1993) investigated the erosion of a scour hole. They derived an equation for an oblique jet with a scour hole filled with water. In principle, the Stein equation is similar to the Hoffmans equation.

Obviously, the strength of the grass cover is relevant. In the upper 0.05 m to 0.2 m the combined effect of roots and clay determine the strength, while at larger depths the clay only will contribute. Between the soil surface and about 0.1 m the strength decreases to a minimum strength at a depth of about 0.1 m where the number of roots decreases significantly. Below the minimum value the strength increase again. This varying strength is not included by Hoffmans and Stein. Valk (2009) presented a model that does take this infuence into account by a depth-depending strength based on the diminishing number of roots with depth by using the dimensionless root area, resulting:

$$\tau_c(z) = C_{clay,c} + C_{grass,c} \tag{11}$$

where $\tau_c(z)$ is the depth depending critical strength (N/m^2), $C_{clay,}$ is the critical shear strength of clay (N/m^2), and $C_{grass,c}$ is the critical strength of grass (N/m^2).

Valk (2010) also estimated the decreasing hydraulic jet impact due to a scour hole filled with water:

$$\tau_0(z) = \tau_0\, e^{-z/\ell_w} \tag{12}$$

where $\tau_0(z)$ is the hydraulic load at depth z, τ_0 is the hydraulic load at the surface, z is the depth, and ℓ_w (= 4 m) is a length scale accounting for the damping of the jet in the scour hole.

Valk combines both equations in an erosion rate formula with a load $\tau_0(z)$ due to the overflowing water, and a strength $\tau_c(z)$ related soil resistance against erosion. This allows directly to calculate the development of scour in time.

IV CONCLUSIONS

In the last five years many wave overtopping tests have been carried out in order to determine the strength of the grassed inner slope during extreme conditions (Van der Meer et al, 2009, 2010). The tests showed that transitions from a slope to a horizontal are more vulnerable to erosion than the slope itself. Erosion was observed already for overtopping discharges less than 10 ℓ/s per m width, while for an undisturbed slope hardly any erosion occurred for discharges of 30 ℓ/s per m. In particular, if a pavement consisting of bricks or open concrete blocks on a sandy under layer is present on the berm or at the toe, considerable scour can be expected.

The erosion at transitions is tested at three locations. Table 1 gives some qualitative details of the tests carried out and the observed erosion at the transition.

Test location	Characterisation of transition	Quality of grass cover and soil	Observed scour
Kattendijke	Minestone road on a sand bed	Good grass on clay, but many mole holes	1.0m
Afsluitdijk	Brick road	Average grass on good clay	0.3m
Vecht	Road consisting of concrete blocks	Good grass on sand	0.5m - 1.0m

Table 1 Data of tests regarding erosion at transitions in dike slopes

The erosion has been predicted with the jet scour equations such as the one of Hoffmans, i.e. Eq.10. This results in the following scour depth with the critical flow velocity estimated on the basis of quality of the grass cover and the soil:

- Kattendijke: 0.7m – 1.3m (with U_C = 2 to 4 m/s)
- Afsluitdijk: 0.3m – 0.5m (with U_C = 6.3 m/s)
- Vecht: 0.6m – 0.8m (with U_C = 4 m/s)

Comparing the predicted and observed scour the similarity between the results is obvious. The order of magnitude is the same. It should be noted that the outcome of Eq.10 is very sensitive for the value of the critical flow velocity. It can be concluded that Eq.10 is applicable for the prediction of the final scour depth at transitions in dikes but it requires careful considerations knowing the limited number of tests on which the formula is based.

No comparison of predicted and observed damage is made with the damage equation based on the cumulative effective hydraulic load with Eq.8. The reason is that only during the tests at the Vecht the initial erosion and the development of the scour depth during the tests has been measured. For the other tests only the final scour depth at the end of the tests has been determined. This limited number of tests does not allow to determine the damage number D and the validation of the parameter α_m in Eq.8. Future tests that are scheduled will allow to validate this formula.

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