DAMAGE TO GRASS COVERED SLOPES DUE TO OVERTOPPING

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Many dike failures have been ignited by damage due to erosion on the landward slopes. This paper investigates how grass covered slopes perform when being attacked by overtopping flow during storm surges. Based on observations during a number of simulator tests, damage is classified into three types 'head-cut', 'roll-up' and 'collapse' depending on the combination of grass, material components and corresponding layer thickness. To quantitatively predict the potential types, strength ratio and thickness ratio are proposed. Besides, erosion usually starts at weak spots so their spatial distributions are evaluated along dike stretches with various lengths. Finally, the overtopping resistance of a grass turf is presumably represented by critical velocities depending on soil cohesion and apparent cohesion induced by roots. The computed results are comparable to erosion on Bermuda and Carpet grass slopes tested with the simulator.

Keywords: slope; grass; overtopping

INTRODUCTION

Heavy erosion of grass covers might reduce the stability of landward slopes, hence threatening the functionality of dikes. Attacked by some 6 to 8 storms every year, Vietnamese sea dikes have breached times leading to serious inundation and loss of life. Many of dike failures start with erosion on the inner slopes. Solutions are higher dikes to reduce overtopping and/ or more resistant landward slopes to increase strength. Therefore, more understanding of slope erosion induced by overtopping flow is encouraged in attempts to improve the existing sea dikes.

The presence of grass helps to improve the erosion resistance of dikes as well as in case of earth surfaces in general (e.g., Cornish et al., 1967; Hewlett et al., 1987). A number of studies using wave flume experiments and in *situ* tests have shown the surprising increase in erosion resistance of a slope once a dense root network is established (Piontkowitz, 2009; Van der Meer et al., 2009; Steendam et al., 2010; Trung et al., 2012). Normally, strength of a grass covered slope is characterised by a mean overtopping discharge with associated duration of application. For example, several hours applying discharges of less than 10 l/s per m is not able to cause a Dutch grass dike to fail (Steendam et al., 2008). In addition to a representative strength, several damage manners are observed to take place on various slopes such as 'head-cut' and 'rip off' (e.g., Van den Bos, 2006; Valk, 2009). However, a general classification of damage would seem to be missing. Every manner is likely to occur under a certain circumstance and might probably be indicated by measurable parameters.

In Vietnam, tests with the simulator have shed light on how grassed slopes react with overtopping flow for the past several years. Besides, cumulative data on soil and root properties have been collected and analysed. These findings should be explored further to gradually understand and better appraise the potential strength of grass in protecting dikes. It is worth noting that a large part of the landward sea dike slopes is still covered with grass in Vietnam (e.g., Trung et al., 2012).

Therefore, the paper intends to evaluate the performance of grass covered slopes under attack of overtopping. The study classifies manners of damage that might take place on slopes of different specifications such as layer thickness and material composition. To predict the potential manners, indicators are proposed with regard to the shear strength and thickness of the slope layers. Additionally, spatial distribution of weak spots where erosion usually initiates is discussed. Finally, the study estimates the strength of grass turfs expressed by critical velocities, which are provided by soil cohesion and root tensile strength.

TESTING DIKE SLOPES WITH THE WAVE OVERTOPPING SIMULATOR

To assess the strength of real dike slopes, the concept of a wave overtopping simulator was first developed in the Netherlands and has been transferred to USA and Vietnam (Van der Meer et al., 2006, 2008; Trung et al., 2010; Thornton et al., 2011). The simulator is able to produce (simulate) overtopping waves, i.e. also overtopping flow, on the dike crests and landward slopes. By doing so, overtopping induced erosion can be simulated on real slopes under normal conditions of weather. Since 2007, river and sea dikes have been tested with the simulator at more than twenty locations across the Netherlands and Belgium.

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In Vietnam, tests were performed on Thinh Long and Thai Thuy sea dikes; and Yen Binh dike which was built with a 1/15-inclination slope. In Thinh Long, the first section was covered by Bermuda grass only. Meanwhile, a combination of Bermuda and Carpet grasses was found at the second and third ones. Additionally, there were several Casuarina trees with diameters of centimetres. Three sections were protected with a mix of Bermuda and Vetiver grasses in Thai Tho. In general, Bermuda and Carpet grasses form a continuous mat lining over the soil surface, whilst Vetiver grass grows in separate clumps scattering spatially. Vetiver with strong and long roots is durable and is commonly used in slope stabilisation (e.g., Truong et al., 2008).

During each test, the simulator generates a certain number of overtopping waves to simulate a storm of interest. And each storm can be characterised by given wave conditions and a mean overtopping discharge as described in the overtopping manual EurOtop (Pullen et al., 2007). A number of reports and proceedings are available providing very much details of the set-up and results of all these tests. Observations show that erosion often starts or enlarges at the transitions between slope and toe, the transitions between different materials, around objects and weak spots. The next section will explore and classify different mechanisms of damage to grass covered slopes due to overtopping.

CLASSIFICATION OF DAMAGE

Under impact of overtopping flow, shallow trench and small hole might be created with a depth of several centimetres at potential positions as described above. Keep loading further with sufficient energy, damage tends to extend in different manners as observed during a large number of simulator tests. Various combinations of grass, soil type and layer thickness would lead to three distinctive types: *a*) 'head-cut', *b*) 'roll-up' and *c*) 'collapse'. The first two frequently occur on the landward slopes in Vietnam while the last one seems to be predominant on the sandy dikes in the Netherlands. It is worth noting that the damage discussed here does not immediately lead to the dike failures at functioning as sea defence. However, the slopes are destroyed to the extent that it is still feasible to repair/ recover later.

Damage type 'head-cut'

In the north of Vietnam, sea dike is usually constructed of a clayey layer and a sandy core (e.g., Trung et al., 2012). The quality and thickness of the clayey layer varies from area to area, and even within a short stretch. Test results at Thinh Long might provide an obvious example of these variations. Note that only the top layer of about 20 cm thick is reinforced by roots, as widely reported in many studies (e.g., Sprangers, 1999; Stanczak et al., 2007; Trung, 2012b). At all three sections of Thinh Long, several minor eroded spots were enlarged in both surface area and depth to expose the underneath soil. Then the grass turf and the clayey body were likely to be eroded instantaneously. This can be explained by the similar resistance against flow of these layers. Aggregates of root penetrated soil and lumps of clay were subtracted from the dike body, thus resulting in visible holes with relatively vertical walls. These holes might extend through the clayey layer, which was about 80 to 100 cm thick, toward the inner core. This destruction manner is defined as 'head-cut' and sketched in Fig. 1.
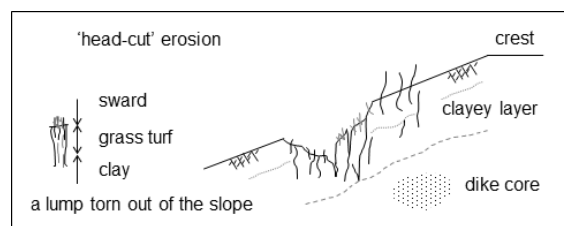

Figure 1: Damage type 'head-cut', grass turf and clayey layer underneath are torn out of the slope simultaneously.

Valk (2009) emphasised the dominance of 'head-cut' erosion on a landward slope, especially around its toe. However, material composition appears to play a decisive role rather than positions because the mechanism took place both on the steep part and at the toe as observed at Thinh Long. Do Son and Thai Tho dikes also witnessed a similar manner on the Vetiver grass slopes. More demonstrations can be found in other technical reports (e.g., Trung, 2011). Site investigations indicated that Vetiver roots mainly develop

in vertical direction, i.e. they predominantly penetrate downward rather than laterally. For this reason soil aggregates bonded with roots are torn out of the surroundings mostly in vertical direction.

As we have seen, 'head-cut' type often occurs on a clayey layer which is considerably thicker than the grass turf itself. It is hypothesised that the erosion resistance varies slightly within this thick clayey layer so that lumps including soil with and without roots are extracted instantaneously and vertically. This distinguishes 'head-cut' from other manners such as 'roll-up' and 'collapse', where the grass turf is far different in strength compared to the materials underneath.

Damage type 'roll-up'

Fig. 2 illustrates the enlargement of two eroded areas at section Yen Binh 4. Under flow rates of 80 and 100 l/s per m, the left bare strip extended about 1 m downward. Pieces of the turf were turned up side down at the edges of these two eroded areas.
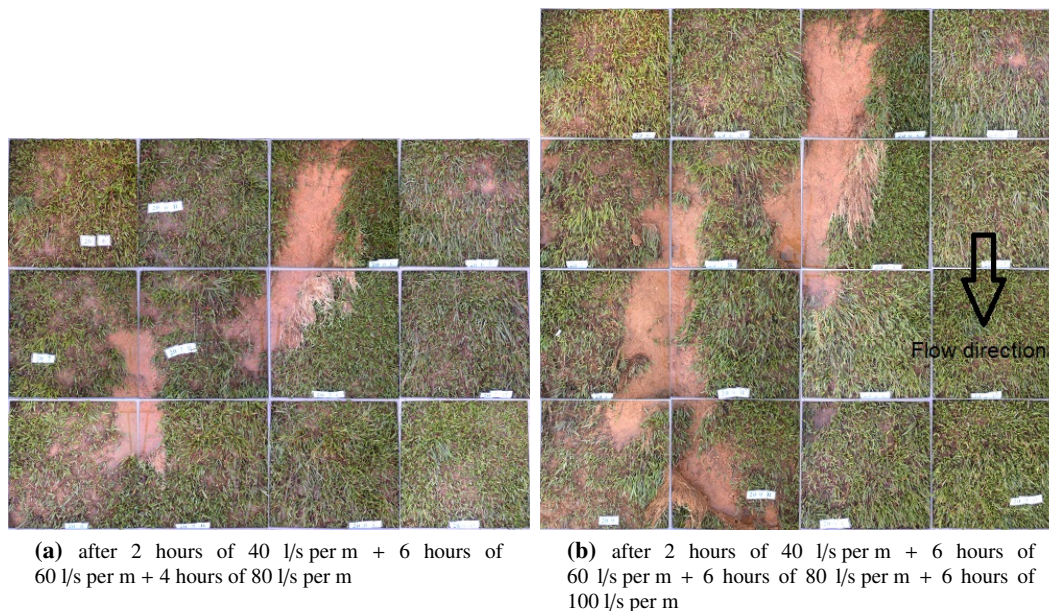

(a) after 2 hours of 40 l/s per m + 6 hours of 60 l/s per m + 4 hours of 80 l/s per m

(b) after 2 hours of 40 l/s per m + 6 hours of 60 l/s per m + 6 hours of 80 l/s per m + 6 hours of 100 l/s per m

Figure 2: Section Yen Binh 4, surface erosion around the dike toe due to increasing discharges. Flow direction is from top to bottom.

Similarly, the top layer of about 5 to 10 cm, where most roots concentrated, was cut underneath and lifted up at other positions across the Yen Binh slope. The turf was swept away to expose the soil body that classified hard clay (see Trung, 2012a). Fig. 3 sketches this mechanism what was described as 'roll up' or 'turf set-off' in previous works (Hewlett et al., 1987; Young, 2005). This shallow erosion is comparable to the mode of 'bulging' as observed at Boonweg dike, Friesland, the Netherlands. Where several hours of 75 l/s per m flushed out a part of the grass turf revealing a hidden path constructed of brick stones (Van der Meer et al., 2008).
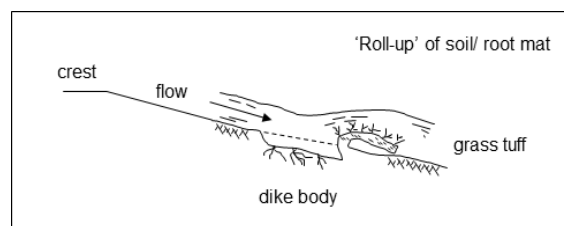

Figure 3: Damage type 'roll up', grass mat is cut underneath and pushed up gradually (modification of Hewlett et al., 1987).

After formation, the initial damage might probably extend toward the dike body below or limit within the grass turf. In the later case, overtopping flows seem to be insufficiently energetic to destroy the layer underneath. However, drag forces induced by flow gradually tear and lift up the leading edge of the grass sod to enlarge the surface damage downward. Hoffmans (2012) investigated a similar phenomenon and developed the turf element model. In which the *load* is generated by the pressure fluctuations due to the flow turbulence while the *strength* is a combination of soil weight, friction, and root tensile. The authors pointed out that when the minimum soil normal stress falls within the grass turf and the load is large enough, a 'bulging' mechanism might occur. Nevertheless, observations at Yen Binh suggest that critical strength should find its minimum under the grass turf and just above the hard clayey body. In other words, resistance of the protected soil is temporarily greater than that of the grass sod at its bottom, thus limiting the damage extension.

Although, 'roll-up' took place on slopes covered with both Bermuda and Carpet grass, the mechanism was found to be different depending on the characteristics of each species. Within the first 10 cm under the soil surface, Carpet roots distribute more regularly in diameter and density while Bermuda roots tend to get thinner and fewer (e.g., Tuan, 2012; Trung, 2012a). Besides, Bermuda grass creeps on the ground and roots wherever a node reaches the ground, forming a mat of stems and blades. In general, this species is likely to be broken stem by stem or a group of stems which are close to each others. To contrast, due to the dense mat of roots, Carpet grass works as a united mat which is often lifted and rolled up at weak positions by drag forces as in Fig. 2.

Damage type 'collapse'

The third type was recognised at St. Philipsland, Zeeland, the Netherlands. The outer layer of about 40 to 50 cm thick was severely eroded under a flow rate of 50 l/s per m, thus directly revealing a sandy core. Water easily flushed out part by part of the core in a short period as sand is non-cohesive. Aggregates torn out from the grass turf were free to fall to the sand below. It is the response of the slope to overtopping flows that inspires the name 'collapse'. Fig. 4 demonstrates this manner when the erosion magnitude of sand is still moderate. Of course, the top layer including the turf hold a certain strength but the layer was relatively thin and based on a sandy core. The 'collapse' is stimulated by considerable difference between these two layers in resistance to flows.
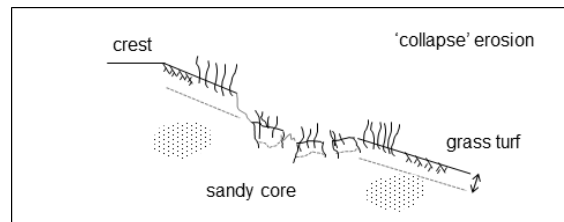

Figure 4: Damage type 'collapse', grass turf is damaged to immediately expose the sandy core underneath.

DAMAGE INDICATOR
Successive phases of damage

In practice, more than one single type are sometimes found to occur on one slope in a specific sequence. On the one hand, slopes are constructed of several layers of (possibly different) materials with a great variation in resistance. The core material is protected by a grass cover, which consists of a top soil and subsoil (e.g., TAW, 1997). On the other hand, overtopping is a natural phenomenon that can stop or continue unexpectedly, thus resulting in a uncontrollable magnitude of damage. Therefore, the material composition of a slope and the random process of waves might probably interact to stimulate different mechanisms throughout consecutive phases. Section 4 of the Boonweg dike in Friesland gives an example of how damage develops over three phases (Steendam et al., 2008; Van der Meer et al., 2008). After 5 hours applying 75 l/s per m, two large bulges were formed and then pulled apart to reveal a clayey surface underneath, i.e. the first phase - 'roll-up'. 'Head-cut' quickly took over the thin clayey layer leading to a large hole with very steep slope in the second phase. Sand was flushed out of the core leaving hollow space below the grass cover. In the third phase, lumps of clay progressively 'collapse' due to their self weight and the flow attack. The test stopped about 45 minutes after the first damage was recognised. Note that

all simulator tests always ended before the damage could threaten the global stability of the slopes under investigation.

The presence of three layers the top soil, where most of roots are found, the sub soil and the sandy core make three mechanisms happen on one slope like at Boonweg. When the core material is clay instead of soil, 'collapse' is not likely to take place but 'head-cut' would seem to be prevalent. Conditions facilitating each type of damage have been qualitatively examined. To quantitatively distinguish these mechanisms, the next subsection will propose measurable parameters.

Strength ratio

Many studies have found that soil is strengthened by grass roots (Wu et al., 1979; Schmidt et al., 2001; Stanczak and Oumeraci, 2012). It is because roots provide an additional cohesion to soil. Within a turf, the greater the number of roots (higher density) the greater does the total cohesion become. Measurements also revealed that the number, volume and weight of grass roots decrease with increasing depth under the soil surface (e.g., Sprangers, 1999; Trung, 2012b). Besides, a root thread can resist a pulling force F_p in order of several Newton (Cheng et al., 2003; Stanczak et al., 2007; Trung, 2012b). If all roots are assumed to resist the same breaking force and work simultaneously, the total tensile strength generated at a certain depth d can be expressed as:

$$\sum \tau_r = n_r \times F_p \times \frac{1}{a_s} \tag{1}$$

where n_r is the number of roots at d and $a_s = \pi \times r_s^2$ [10^{-6}m^2] is the sample area with a radius r_s [mm] where roots are counted. Several guidelines and reports describe how to investigate the number and strength of grass roots on dikes (Sprangers, 1999; VTV, 2006; Trung, 2012b).

As discussed in the preceding subsections, the relationship between the flow resistance of the subsoil and the turf mainly governs how damage happens. If the shear strength is considered to represent the resistance, a ratio between the cohesion of the subsoil c_{ss} and the turf c_{turf} can be proposed. Besides, the thickness ratio between these two layers d_{ss}/d_{turf} seems to exert some influence. The two ratios as defined in Fig. 5 are used to quantitatively classify damage types as follow.
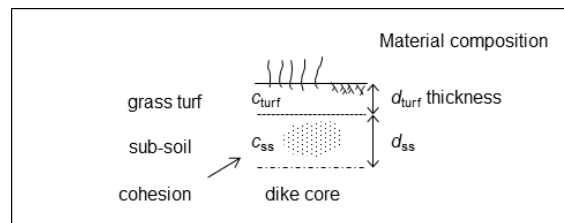

Figure 5: Material composition of a slope including a grass turf (thickness d_{turf} and cohesion c_{turf}), a subsoil layer (c_{ss} and d_{ss}) and a core.

Table 1 summarises material specification and damage description of the simulator tests in Vietnam and the Netherlands. In which the quality of grass is classified according to VTV (2006). The number of roots n_r is taken on an area with a diameter of 30 mm and at 10 cm under the soil surface. Note that all turfs are assumed to be 20 cm thick. Within the grass turf, soil cohesion is neglected and the root tensile strength is assumed to solely contribute to the turf cohesion. Therefore, c_{turf} is replaced by $\sum \tau_r$ which is calculated with Eq. (1) above.

In Viet Nam, only Bermuda roots are taken into account at Thinh Long and Thai Tho with a breaking force F_p of 5.86 and 5.39 N, respectively. At Yen Binh, a value of 2.11 N is applied for both Bermuda and Carpet roots. In case of a clayey dike as Thai Tho and Yen Binh, the subsoil layer is much thicker than the grass turf so d_{ss}/d_{turf} is given a rough estimate of 10. Shear tests provide the soil cohesion as given in Table 1.

In the Netherlands, Vechtdijk is a sand dike so there is no subsoil layer. The sand core has a zero cohesion and is considerably thicker than the turf, i.e. the thickness ratio is 10. The breaking force is converted from a root diameter of $d_r = 0.13$ mm and a tensile strength of $\tau_r = 20 \times 10^6$N/m^2 (Hoffmans et al., 2008). The clay cohesion is estimated with regard to the erosion categories given in TAW (1996)

as follows. A clay of erosion-resistant, i.e. category C1, has a cohesion of $18.75 \times 10^3 \text{N/m}^2$ (soft clay, $c = 12.5 \sim 25 \times 10^3 \text{N/m}^2$). A little erosion clay, category C3, has $10 \times 10^3 \text{N/m}^2$ (very soft clay, $c < 12.5 \times 10^3 \text{N/m}^2$).

Fig. 6 shows the relationship between c_{ss}/c_{turf} and d_{ss}/d_{turf}. Results are separated into two graphs because dikes (grass and soil) are different in Vietnam and the Netherlands. With greater values of c_{ss}/c_{turf}, the grass covers at Yen Binh were 'rolled up' while the 'head-cut' type took place at Thinh Long and Thai Tho. A limit of 0.5 is proposed to distinguish between the two types. Lying on the vertical axis, i.e. $c_{ss}/c_{turf} = 0$, the Vechtdijk grass cover failed with the 'collapse' manner. With strength ratios greater than 2, the grass mats were first ripped off and might be eroded in the 'head-cut' type in the next phase as at Boonweg, Kattendijke and Delfzijl. After 'head-cut', 'collapse' caused a recognisable erosion on St. Philipsland dike. Unlike the Vietnamese cases, the border is not obvious between a 'head-cut' and a 'roll-up' on these Dutch dikes. In other words, they are sometimes exchangeable. However, a limit of 1.5 is suggested to distinguish the two manners from a 'collapse'.
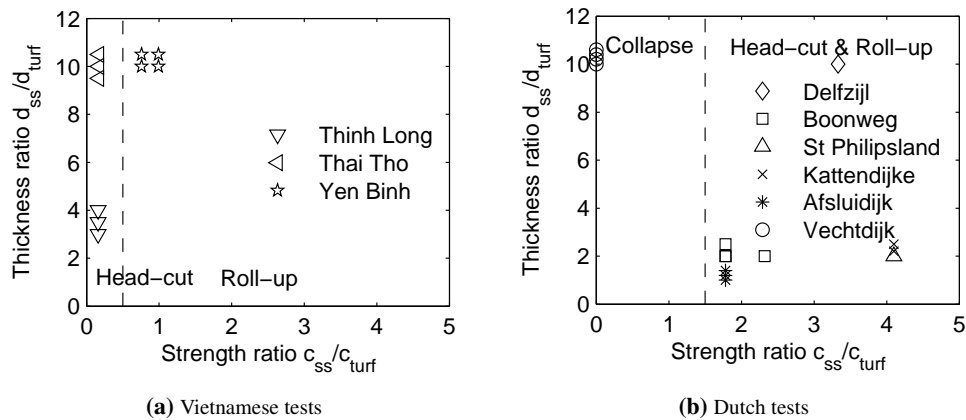

(a) Vietnamese tests   **(b)** Dutch tests

Figure 6: Damage is classified regarding to the strength ratio c_{ss}/c_{turf} and the thickness ratio d_{ss}/d_{turf} of a grass covered slope.

In general, the greater the strength ratio, the higher the possibility that the 'head-cut' and 'roll-up' types may happen. When the strength ratio goes towards zero, a dike slope is likely to 'collapse'. Besides, the corresponding thickness ratios are usually high. If more than one types take place, they should follow a sequence from a 'roll-up' or/ and a 'head-cut' ⇛ a 'collapse'. On the horizontal axis, the strength ratio decreases from right to left. Meanwhile, the thickness ratio goes downwards becoming smaller. Remarkably, this sequence is irreversible, i.e. the 'collapse' of a grass cover might probably lead to a slope failure, and neither a 'roll-up' nor a 'head-cut' can take place afterwards.

DISTRIBUTION OF WEAK SPOTS

Tests with the simulator revealed that erosion often takes place at bare spots and around objects emerging from a slope. Here a bare spot is defined as an area of at least 10 cm by 10 cm covered with no grass as in Fig. 7; and an obstacle such as a tree should be some 10 cm in diameter. Thus the occurrence of damage increases with more frequent appearance of the vulnerable positions (e.g., Van den Bos, 2006). Experimentally, the ratio of the number of severely damaged spots n_{dam} to the number of bare spots n_{weak} can be determined. After testing with the simulator, the first section of Thinh Long had 5 heavily eroded spots out of 12 bare spots (5/12); the ratios were 4/6 and 2/7 at the other two. Therefore, $n_{\text{dam}}/n_{\text{weak}}$ was 0.46 on average, i.e. 46% of the weak spots became considerable damage within a stretch of 50 m long.

As an attempt to evaluate the potentially weak spots, observations were made for 5 sections along the Hai Hau dike in Nam Dinh province. Number of weak spots on every cell of 2 m^2 were counted (1 m along the dike stretch); pictures were also captured. Bush and Casuarina trees were sometimes found as well. A Casuarina with diameter of about 10 to 15 cm and an area of 0.1 m^2 covered with bush is assumed to be equivalent to 1 weak spot. Fig. 8(a) shows the probability density of weak spots at sections TL4, TL5, TL6,

Figure 7: A weak spot on Thai Tho grass slope, the bamboo frame is 1 m × 1 m.

NC1 and NC2 with lengths of 27, 11, 66, 30 and 24 m, respectively. The number of the weak spots across 2 m^2 varies strongly along every stretch. And the largest value of n_{weak} may fall in a range between 10 and 25.
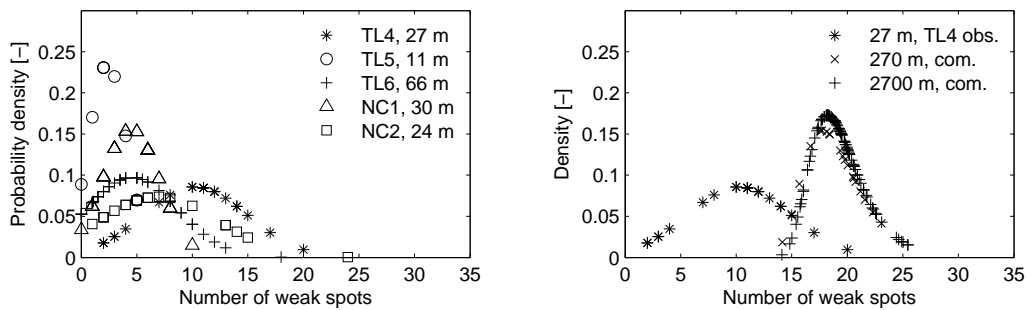
(a) 5 observed stretches of the Hai Hau dike with lengths varying from 11 to 66 m

(b) lengths of 27 m (section Thinh Long 4, observed), 540 m (computed) and 2700 m (computed)

Figure 8: Probability density of the number of weak spots on an area of 2 m^2 along stretches of various length.

A good cover of grass usually eliminates the slope erosion due to overtopping, such as at Yen Binh. A greater number of weak spots may lead to a higher probability of damage. Hence it is worth to assess the maximum value of n_{weak} along a dike stretch.

Vrijling and van Gelder (2006) estimated the correlation lengths of the water level at sea and the oscillations to be 50 - 100 km and 5 - 10 km, respectively. A part of a coastal defense, e.g. a dike stretch, can be considered as a series system of correlated elements with high correlation in load, and low or no correlation in resistance (Kanning, 2012). As a result, the greater number of elements, the higher the probability of failure. This is known as the length-effect.

Along the Nam Dinh coastline, the area between two dike routes are often divided into parts by transverse dikes with a distance varying from 500 to 3000 m (Vinh et al., 1996). As a result, a dike route consists of some shorter stretches. Each stretch is assumed to be a series system of a certain number of sections, which are statistically independent. A stretch of 500 m can be modelled by some 20 sections with length of 25 m each while a 3000 m one presumably consists of some 100 elements of 30 m long each. To simulate these, two sets of respectively 20 and 100 realisations are generated from the TL4 observation (27 m long).

Fig. 8(b) depicts the probability density of the maximum number of weak spots along two dike stretches of 540 and 2700 m long, respectively. The real observation (parent distribution) obtained at TL 4 is also plotted for comparison. Obviously, the longer the stretch (more sections are present) the further the maximum value may shift rightward, 20 spots for a 27-m-long stretch versus 25 for a 540-m-long one. As a result, there might be respectively 9 and 11 positions of severe damage on every area of 2 m^2 along the two

stretches if a ratio of $n_{\text{dam}}/n_{\text{weak}} = 0.46$ is applied (similar to the case at Thinh Long above). Apparently, the damage probability increases when a dike section becomes longer.

CRITICAL VELOCITY OF GRASS TURFS

Previous sections considered a dike slope as a whole, predicting potential types and spots of damage. However, how strong the slope is was not investigated. The present section aims to address the issue but only limits to the grass cover. At a certain position on the landward slope, its grass turf is damaged (eroded) if the flow velocity u_{y_C} exceeds the critical value u_c (if it exists). One can write the limit state function as

$$Z = u_c - u_{y_C} < 0 \tag{2}$$

where u_c and u_{y_C} are actually the *load* and *strength*, respectively. The following paragraphs will elaborate how to determine these two elements.

For non-cohesive materials, formulas of a critical velocity are widely used as a threshold that indicates the stability of particles subject to water flow. However, a critical value does not really exist due to some factors such as the variations in particle diameters and their protrusion positions (e.g., Schiereck, 2003). Under a certain velocity, some particles move but some others do not, and some can also move further than the others. Similarly, damage to a slope may vary from position to position despite similar attacking force as observed throughout a number of simulator tests in the Netherlands and Vietnam (e.g., Steendam et al., 2008, 2010; Trung et al., 2012). Due to the variation in grass quality, overtopping flows might cause damage at some positions rather than the others.

Roots influence (change) the mechanical properties of soil on slope (e.g., Norris et al., 2008). In general, soil that is permeated by roots can be considered as a new material (new soil) with different properties such as density, porosity, void ratio, moisture content, cohesion, … Accordingly, the soil resistance against flow would change as well. The turf-element model (Hoffmans et al., 2008) is applied to determine the critical depth-averaged flow velocity that a grass turf is able to resist. The flow is considered to be hydraulically rough with the depth-averaged turbulence intensity r_0 of 0.2. The clay has a cohesion c_s and the stress in roots is σ_g. According to Hoffmans et al. (2008), one may express the *strength* as

$$u_c = \frac{\alpha_0}{r_0} \sqrt{\Delta g d_{\text{agg}} + \frac{c_s}{\rho} + \frac{\sigma_g}{\rho}} \tag{3}$$

with $\alpha_0 = \sqrt{\alpha_\tau c_0^2} = 0.29$ as $\alpha_\tau = 1/18$ and $c_0 = 1.21$; and $\Delta = (\rho_s - \rho)/\rho$ is the relative density of soil with $\rho_s = 1700$ kg/m^3 compared to water with $\rho = 1000$ kg/m^3. Hoffmans et al. (2008) chose a value of 0.004 m for the size of detaching aggregates d_{agg}. However, soil reinforced by roots is normally torn out part by part consisting of roots and soil particles. The dimension of these detached parts vary widely between millimetres and centimetres, thus resulting in the velocity contributed by the term $\frac{\alpha_0}{r_0} \sqrt{\Delta g d_{\text{agg}}}$ to increase from some 0.2 to more than 1 m/s. In this study, the parameter d_{agg} is not taken into account for the sake of simplicity.

Trung (2012b) investigated systematically how roots penetrate and strengthen soil. Root permeated soil can be assumed to have a cohesion which is influenced by the density and tensile strength roots. And this cohesion can be simply expressed as the sum of the soil cohesion itself c_s and the artificial root cohesion as

$$c = c_s + a_2 \sum \tau_r \tag{4}$$

with the empirical coefficient a_2 depending very much on root properties (Trung, 2012b). Therefore, the parameter σ_g can be replaced by $a_2 \sum \tau_r$ in Eq. (3).

At a distance y_C from the landward crest edge, the *load* - flow velocity u_{y_C} is estimated with equations developed in a previous work. Trung (2014) reanalysed the data of Van Gent (2002) by relating flow velocity with corresponding volume of the water overtopped. Note that volume distribution is calculated using given wave conditions and a mean overtopping discharge during a certain storm duration (Pullen et al., 2007).

To determine whether damage takes place, the probability density of u_c and u_{y_C} will be compared. For illustration, two situations are considered including a regular cover and a bare spot on Yen Binh dike. Flow velocities are calculated with values of discharge and applied duration as similar as possible to the scenarios used for the simulator tests.

On a regular grass cover

Section Yen Binh 2 was regularly covered with one-year-old Bermuda grass; and it could withstand a flow rate of up to 100 l/s per m in hours. After testing, erosion did not develop further than $y_C = 5$ m from the simulator gate, i.e. the grass cover was kept intact from this distance downward (Fig. 10(a)). The limited damage could be due to the decrease in overtopping flow with increasing distance to the crest. Fig. 9 shows the Gamma probability density function (PDF) of the number of roots n_r at Yen Binh 2; and this PDF should be the same across the whole slope, from crest to toe. The soil cohesion is $c_s = 18 \times 10^3 \text{N/m}^2$ and the magnitude of enhancement effect due to roots is $a_2 = 0.16$ (see Eq. 4). Putting these parameters in Eq. (3) together with the PDF of n_r leads to the PDF of the critical velocity (*strength*) u_c as in Fig. 10. All roots are assumed to be able to resist a breaking force of 2.11 N.
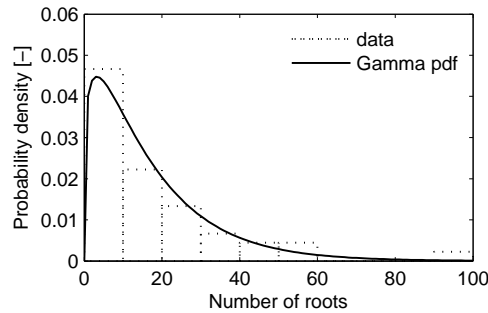

Figure 9: Gamma probability density of the number of Bermuda roots at section Yen Binh 2.

At $y_C = 6$ m, velocities (*load*) u_{y_C} are calculated with discharges of 20, 60 and 80 l/s per m. Every discharge lasts for 4 hours to reproduce as close as possible to the experimental scenarios. The simulator test and velocity computation use the same wave conditions of $H_{m0} = 1.5$ m and $T_p = 6.0$ s. The computed 't location-scale' PDF curve of u_c lies on the right side of those presenting the Weibull PDF of u_{y_C}. The probability of damage is represented by minor areas, which are shared by the u_c curve and the flow ones as in Fig. 10(b). It is implied that overtopping flows were not likely to erode the grass turf at $s_C = 6$ m. The prediction is comparable to the test results described above.

At a bare spot

On the Carpet slope of Yen Binh 3, a top soil layer of 10 cm thick was manually removed on an area of 2 m by 2 m at $y_C = 4$ m from the crest edge. The grass turf was 'rolled up' along the downward border ($y_C = 6$ m) of this man-made erosion after testing with 1 hours of 40, 2 hours of 60, 2 hours of 80 and 1 hour of 100 l/s per m (Fig. 11(a)). Apparently, a large amount of roots concentrated within the top layer was not present. Only roots penetrating deeper than 10 cm still had influence to reinforce soil; and a Weibull function is found to best fit the distribution of these remained roots. A soil cohesion of $c_s = 24 \times 10^3 \text{N/m}^2$ and $a_2 = 0.06$ are applied in Eq. 4. As a result, the bare spot has a 'generalized extreme value' distribution of u_c (*strength*) as shown in Fig. 11(b).

At $y_C = 6$ m, flow velocities are computed with discharges of 40, 60 and 100 l/s per m lasting for 2 hours each. Both the simulator test and velocity computation utilise $H_{m0} = 2$ m and $T_p = 6.2$ s. Fig. 11(b) shows that the u_{y_C} curves do not reach/ cut the u_c one, i.e. the *load* does not exceed the *strength*. Overtopping is predicted not to cause damage to the slope area around $y_C = 6$ m. In general, the calculation slightly underestimates the destructive effect of overtopping flow compared to the experimental result.

Remarks

By comparing the PDFs of critical and flow velocities, the section has determined whether damage takes place at certain positions on a grass cover under a given mean discharge over a duration of time. The proposed method can be used to estimate the potential strength of a grass turf if relevant data on roots and soil is available. However, the model should be improved further to evaluate quantitatively the erosion probability.

(a) real slope situation after testing

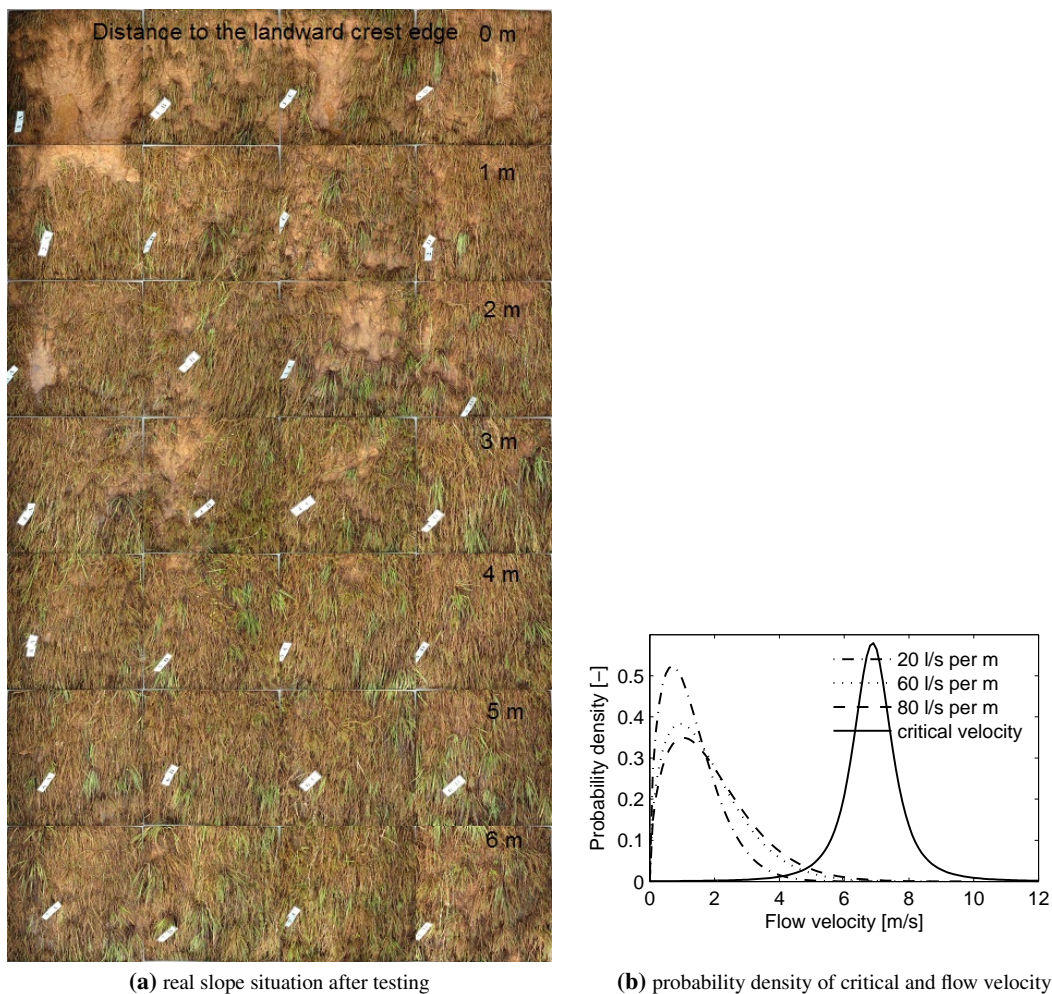**(b)** probability density of critical and flow velocity

Figure 10: Section Yen Binh 2, (a) simulator test with 4 hours 60, 2 hours of 80 and 1 hours of 100 l/s per m; (b) computation for 4 hours discharge of 20, 4 hours of 60 and 4 hours of 80 l/s per m.

CONCLUSION

The paper has sought to investigate the performance of grass covered slopes exposed to overtopping. To this end, two levels were considered the slope as a whole and the grass turf only. First, an attempt was made to explore potential types of damage to the former. Second, the resistance of the latter was evaluated.

At the first level, damage is classified into three main types. When the grass turf and the underneath clayey layer (substrate), which should be sufficiently thick, are similarly resistant against overtopping flow, the mechanism 'head-cut' gets a high opportunity to happen. In the case of a much more durable substrate, erosion is temporarily limited within the turf. This is defined as a 'roll-up'. By contrast, a sandy core is not able to provide a strong support for a thin grass turf in the 'collapse' mechanism. In which soil aggregates are easily extracted from the turf to fall down. In practice, a combination of these three manners may take place on one slope, a 'roll-up' or/ and a 'head-cut' followed by a 'collapse'. Estimating the strength ratio and thickness ratio between the grass turf and the sub-soil layer helps to predict the potential damage.

To investigate the length effect, observations were performed along sea dikes in Nam Dinh province. The longer the dike section the greater the number of weak spots becomes. As a result, the damage probability will increase as it is proportional to this number.

At the second level, the study expresses the strength of a grass turf by critical velocities. Roots usually penetrate to improve the mechanical performance of soil. Therefore, root permeated soil is considered as a new material with new properties, especially its cohesion. The paper estimates the critical velocity taking into account the soil cohesion and the artificial cohesion produced by roots. This critical velocity is the

(a) real slope situation after testing

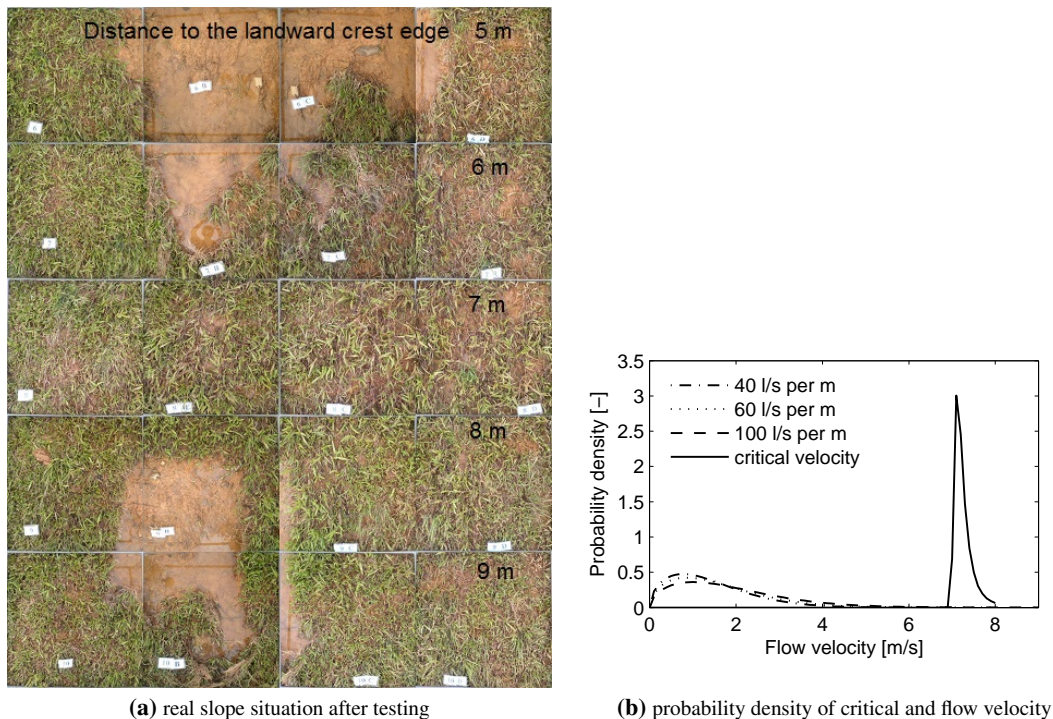**(b)** probability density of critical and flow velocity

Figure 11: Section Yen Binh 3, (a) simulator test with 1 hour of 40 + 2 hours of 60 + 2 hours of 80 + 1 hour of 100 l/s per m; (b) computation for 2 hours of 40, 2 hours of 60 and 2 hours of 100 l/s per m.

strength while the flow velocity associated with a certain overtopping volume is the *load*. At a certain position, the *load* exceeds the *strength* to cause damage to the turf. The approach was applied for a regular position and a bare spot giving results that are comparable to the simulator tests conducted at Yen Binh.

To sum up, the paper has demonstrated an assessment of grass covered landward slopes under overtopping attack. It apparently helps to appraise sea dikes in practice as well as to research root reinforced soil in general. Indeed, more simulator tests and quantitative investigations into roots and soil are encouraged to improve the methods proposed.

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Table 1: Specifications and damage of slopes tested with the simulator in Vietnam and the Netherlands. Erosion resistance of soil is categorised according to TAW (1996) and root quality with regard to VTV (2006).

Section	Dike material	Ero. cat. TAW 1996	c 10^3 N/m^2	Roots VTV 2006	n_r roots	$\sum \tau_r$ 10^3 N/m^2	c_{ss}/c_{turf} -	d_{ss}/d_{turf} -	Damage
Vietnam									
Thinh Long 1	100 cm clay, sand core		20		15	124.35	0.16	4	head-cut
Thinh Long 2	80 cm clay, sand core		20	good	15	124.35	0.16	3	head-cut + fall of the Casuarina
Thinh Long 3	80 cm clay, sand core		20		15	124.35	0.16	3	head-cut
Thai Tho 1			20		15	114.38	0.17	10	head-cut at
Thai Tho 2	clay dike		20	good	15	114.38	0.17	10	concrete
Thai Tho 3			20		15	114.38	0.17	10	beams
Yen Binh 1			34		11.5	34.33	0.99	10	
Yen Binh 2			34	moderate	11.5	34.33	0.99	10	
Yen Binh 3	good clay		34		15	44.78	0.76	10	thin 'roll up'
Yen Binh 4			34	good	15	44.78	0.76	10	
Netherlands									
Delfzijl 1	homogeneous clay dike	C1	18.75	good	15	5.63	3.33	10	gulleys extended to the toe
Delfzijl 3	bare clay	C1	18.75	no root	0	0.00		10	head-cut increased upward
Boonweg 1			12.5	good	15	5.63	2.22	2	grass ripped off at toe
Boonweg 2	60 cm clay, sand core	C3	12.5	good	15	5.63	2.22	2	grass ripped off at toe
Boonweg 3			12.5	moderate	11.5	4.32	2.89	2	large grass ripped off
Boonweg 4			12.5	good	15	5.63	2.22	2	lifting of grass cover; head-cut, collapse
St Philipsland	60 cm clay, sand core	C3	12.5	bad	6.5	2.44	5.12	2	head-cut and then collapse
Kattendijke 1	60 cm clay, sand core	C3	12.5	bad	6.5	2.44	5.12	2	headcut at toe
Kattendijke 2			12.5		6.5	2.44	5.12	2	minor thin ripped off at toe
Afsluitdijk 1	40 cm clay on 100 cm boulder clay	C3	12.5	good	15	5.63	2.22	1	grass ripped off on the entire slope + toe
Afsluitdijk 2			12.5		15	5.63	2.22	1	grass ripped off on slope; damage to the brick path
Afsluitdijk 3			12.5		15	5.63	2.22	1	grass ripped off along the staircase; heavy damage of the staircase; headcut at toe
Vechtdijk 1	15 cm soil on sand core	sand dike	0	good	15	5.63	0.00	10	damage of the road; grass cover eroded at the toe & berm
Vechtdijk 2			0		15	5.63	0.00	10	damage around the tree
Vechtdijk 3			0		15	5.63	0.00	10	thin ripped off and then collapse
Vechtdijk 4			0		15	5.63	0.00	10	thin ripped off and then collapse