WAVE OVERTOPPING RESISTANCE OF GRASSED DIKE SLOPES IN VIETNAM

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The resistance of various grassed slopes against wave overtopping has been appraised by means of the Wave Overtopping Simulator in situ for a couple of years in Viet Nam. Destructive test results show that a dike slope covered with grass could suffer a certain overtopping discharge not smaller than 20 l/s per m. During testing it was difficult to predict when a slope starts to be damaged, however, damages tend to follow a more or less similar process of development. The concept of "erosional indices" and the method of "cumulative overload" (van der Meer et al., 2010) are applied to the simulator tests in Viet Nam. Critical velocities were then estimated for different kind of grassed slopes.

INTRODUCTION

Recent research including in situ tests show that dike slopes covered with grass are able to withstand significant wave overtopping discharges (Van der Meer et al., 2009). It is revealed good grassed dikes are potential protection material in coastal engineering, especially for developing countries. In Viet Nam, resistance of grassed dike slopes against wave overtopping have been investigated by means of the Wave Overtopping Simulator for a couple of years.

Main results of the destructive tests performed at two sea dikes in the North of Viet Nam are presented in the paper. A dike slope covered with grass shows a certain resistance against erosion due to wave overtopping and the maximum discharge varies, but no failure was found for discharges smaller than about 10 l/s per m. Flow measurements were conducted at several locations giving a consistent relation between the flow velocity and the overtopping wave volume.

It was not simple to predict when damage occurs or a grassed slope fails during testing. In order to understand the damage development process of various grassed slopes, the method of "cumulative overload" which was presented by Van der Meer et al. (2010) is applied to the tests in Viet Nam.

WAVE OVERTOPPING SIMULATOR

The Wave Overtopping Simulator was first developed in the Netherlands in order to test real grassed dike slopes in situ, Van der Meer et al., (2006, 2007, 2008 and 2009). With the experience of testing for a couple of years, the original design was adjusted to make the second Simulator, a Vietnamese version. The machine is a water reservoir which can be easily either assembled

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or disassembled and moved from place to place in a short time. When working, the simulator is continuously filled with a certain and constant discharge of water and emptied at predefined moments through bottom valves in a way that the volumes simulate the overtopping wave tongues on the dike crest and then on the landward slope. The maximum capacity is 5.5 m^3/m giving a total volume of 22 m^3 for a 4 m wide simulator. With this size a mean wave overtopping discharge of up to 100 l/s per m can be generated. Figure 1 gives an impression of the Simulator releasing an overtopping wave on the grass slope in situ.

Figure 1. Wave overtopping simulator.

DESTRUCTIVE TESTS

Since 2009, destructive tests have been performed on three sea dikes in the North of Viet Nam. Vetiver grass (*Vetiveria Zizanioides*) and Bermuda grass (*Cynodon Dactylon*) are the most common species on the dike slopes. In Hai Hau - Nam Dinh, the dike slope was covered with mainly Bermuda grass and sometimes Casuarina trees could be found as well. Three slope sections were tested and denoted as TL_01, TL_02 and TL_03. In Thai Thuy – Thai Binh, within a dike stretch of 50 m, a combination of Bermuda grass and Vetiver grass within concrete frames was tested at three locations: TT_01, TT_02 and TT_03 (Figure 2), respectively.

Figure 2. Test point TT_03, mixture of Bermuda and Vetiver grass.

In all tests, the same wave boundary condition was applied with a significant wave height of 1.5 m and a peak period of 6.0 s. Depending on the strength of the grass slopes, the mean discharge was generated varying from small to large: 10; 20; 40; 70; 80; 100 and 120 l/s per m. Each discharge value represents a simulated storm lasting for 4 hours, which is considered representative for storm characteristics in the North of Viet Nam. Overtopping parameters are given in Table 1 with increasing mean discharge.

Table 1. Wave overtopping parameters

	Mean overtopping discharge (l/s per m)						
	10	20	40	70	80	100	120
Crest freeboard R_c (m)	2.27	1.93	1.60	1.32	1.26	1.15	1.06
Percentage overtopping waves P_{ov} (%)	22	33	47	60	63	68	72
Number overtopping waves N_{ow}	152	231	327	412	433	468	495
Maximum overtopping volume V_{max} (l/m)	1330	1900	2860	4120	4520	5300	6060

MAXIMUM WAVE OVERTOPPING DISCHARGE ON GRASS SLOPES

In Nam Dinh, the three test sections showed various resistances against wave overtopping where the maximum applied mean wave overtopping discharge was found significantly different from section to section. At section TL_01, the maximum discharge was 70 l/s per m, while a much lower value of 40 l/s per m was tested at the third section TL_03. A combination of Bermuda grass and a 7-cm-diameter Casurina tree at TL_02 failed at a moderate discharge of 20 l/s per m. Within 50 m of a sea dike stretch in Thai Binh, the three test sections could stand more or less similar maximum overtopping discharges of about 100 l/s per m and even larger. The maximum wave overtopping discharges at six test sections with soil and grass specifications are given in Table 2. It should be noted that at the end of each test the grass slopes were damaged significantly and the dike stability was threatened.

Table 2. Maximum wave overtopping discharges on grassed dike slopes, l/s per m				
Section	Grass	q_{max}	Grass age	Clay quality
TL_01	Bermuda	70	4 years	moderate
TL_02	Bermuda, Casuarina	20	4 years, 2 years	moderate
TL_03	Bermuda	40	4 years	moderate
TT_01	Bermuda, Vetiver	100	> 4 years, 6 months	good
TT_02	Bermuda, Vetiver	120	> 4 years, 6 months	good
TT_03	Bermuda, Vetiver	100	> 4 years, 6 months	good

HYDRAULIC MEASUREMENTS

During destructive tests, hydraulic measurements were carried out in order to determine the flow parameters such as flow depth and flow velocity on the grass slope. Each measurement consisted of three times replicating the same wave overtopping volume varying from 500 l/m to 5000 l/m. This paper focuses on the hydraulic overload method, in which the flow velocity primilarily governs the damage process, therefore, only the flow velocity is presented hereafter.

Set-up and analysis

Flows released from the Simulator are discontinuous and moreover very turbulent with high density of air bubbles. Conventional instruments used in the laboratory are not designed to measure characteristics of this kind of flow. A digital camera was applied to capture the front velocity on the dike slope. Based on the differences in positions of the front part of the overtopping flow over a certain distance, and with the time delay between successive images, front velocities can be derived. Van der Meer et al. (2010) found that front velocities represent well the velocity at the top of the flow as well as the depth-averaged velocity in the layer. Measurements were implemented at two positions between $x = (2 \sim 5)$ m and $x = (5 \sim 8)$ m with x is the distance on the slope from the dike crest.

To analyse the front velocity movies of water flowing on the dike slope were watched at a low speed or in sequence of frames. It can be seen in Figure 3 that the front part of a 500 l/m flow traveled over a distance of 3 m within 0.8 seconds giving a front velocity of 3/0.8 = 3.75 m/s.

Figure 3. Movement of the front of a wave over 3 m within 0.8 s, giving a front velocity of 3.75 m/s.

Results

Figure 4 graphically demonstrates the front velocity, u, versus the overtopping wave volume, V, obtained from hydraulic measurements at four test locations in Nam Dinh and Thai Binh. In general, increasing volumes generate higher flow velocities on the dike slope and a relation between the front velocity and the overtopping wave volume and can be given by:

$$u = 4.0V^{0.2} \quad (u \text{ in m/s and } V \text{ in m}^3\text{/m}) \tag{1}$$

This relation is slightly different from what was found by Van der Meer et al. (2010), where the coefficient was 5.0 and the power was 0.34 as follow:

$$u = 5.0V^{0.34} \tag{2}$$

This difference can be due to the difference in geometric specfication of the dike cross sections in the Netherlands and Viet Nam. Equation (1) is used in all further calculation in this paper.

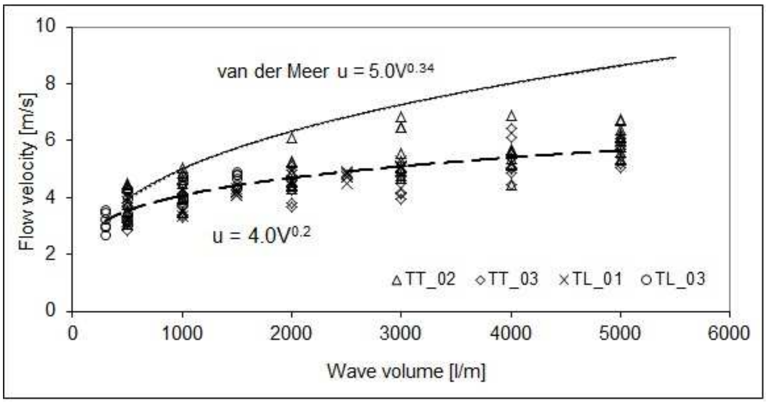

Figure 4. Front velocity on the slope as function of overtopping wave volumes.

EROSIONAL INDICES

Base on destructive test results at the Vechtdijk, Van der Meer et al. (2010) introduced four damage criteria of a grassed slope including: First damage, Various damaged locations, Failure and Non-failure after testing. The first three criteria could be observed at test sections in Viet Nam while the Non-failure criterion was not recognised as all the tested slopes were severely damaged after testing. Figures 5, 6 and 7 give an impression of different damage criteria on various grassed slopes which, were tested with the Wave Overtopping Simulator in Viet Nam. A practical development on erosional resistance was applied over the Dutch dikes, see Van der Meer et al., 2010. The cumulative overload was defined, including a critical velocity for a certain grass covered slope. In this paper, the method is first calibrated with the test results in Thai Thuy – Thai Binh and then the verification will be made by using results in Hai Hau – Nam Dinh.

Figure 5. First damage on a Bermuda grass slope, section TL_03.

Figure 6. Various damages on a mixed grass slope, section TT_03.

Figure 7. Failure of a Bermuda grass slope, section TL_01.

Calibration of cumulative overload method

The Thai Thuy – Thai Binh dike is constructed with good clay, the dike crest level is at +5 m above MSL and 6.0 m wide, paved with concrete of 20 cm thick. The grassed slope is 9 m long from crest to toe and the inclination is 1:3. Bermuda grass was about 4 to 5 years old while Vetiver grass was planted in May, beginning of the rainy season and about 6 months before testing. It is recommended to grow Vetiver from young plants and the time of planting should be scheduled during the rainy season (Robert). Three slope sections were selected with different quality of grass cover and different configurations of the concrete frame. At section TT_01, the first damage happened after 4 hours tests with 20; 40 and 80 l/s per m. The slope failed after that 4 hours of 100 l/s per m. Section TT_02 showed a similar resistance when the first damage occured after 4 hours tests with 20; 40 and 80 l/s per m. A discharge of 120 l/s per m was then applied resulting in the slope failure after 1 hour of testing. The third section TT_03 showed earlier damage after 4 hours tests with 20 and 40 l/s per m and 2 hours of 80 l/s per m. After 2 more hours of 80 l/s per m, various damages could be observed on the slope, as can be seen in Figure 6. The third section failed after 2 extra hours testing with 100 l/s per m.

With known distributions of overtopping wave volumes (see EurOtop Manual, 2007 for details) and known velocities of each overtopping wave volume (Eq. 1), it is possible to compute the cumulative overload for each wave overtopping condition, or a number of tests, to a certain moment when a damage criterion is reached with the following equation:

$$\sum\left(u^2 - u_c^2\right) \qquad [m^2/s^2] \qquad (3)$$

The first damage criterion is not a consistent parameter as it may depend on whether a weak spot does exist on the slope surface under investigation. The second criterion “various damaged locations” was only observed at test location TT_03. Therefore, the third criterion “Failure” with cumulative overload value of 3500 [m^2/s^2] was used to compute the critical velocity at three test locations in Thai Binh. A critical velocity of 4.0 m/s, which was derived from a process of trial and error, that gives a correct value of 3500 [m^2/s^2] for Failure criterion at TT_01, TT_02 and TT_03, respectively. The overtopping wave volume that in accordance with this velocity is 1.01 m^3/m. When critical velocity of 4.0 m/s is applied, the first and second damage criteria get the following values:

First damage: $\sum\left(u^2 - u_c^2\right)$=1812 [$m^2/s^2$] wrt 500 [$m^2/s^2$] in Vechtdijk

Various damages: $\sum\left(u^2 - u_c^2\right)$=2076 [$m^2/s^2$] wrt 1000 [$m^2/s^2$] in Vechtdijk

The large discrepancy between results in Thai Binh and Vechtdijk of the First damage and Various damaged locations criteria can be explained by the sandy body of Vechtdijk dike while in Thai Thuy – Thai Binh the dike was constructed with good clay and covered with a mixture of 4-year-old Bermuda grass and 6-month-old Vetiver.

Another calculation was also made by using Equation (2) derived from hydraulic measurement of Van der Meer et al. (2010). To satisfy the condition of Failure criterion, a much higher critical velocity of 6.0 m/s was found. As a result, the first and the second criteria get smaller values, which are alternatively 1539 [m^2/s^2] and 1802 [m^2/s^2], compared to those obtained by using Equation (1), see Figure 8 and Figure 9. It can be seen that different way of transforming flow velocity may considerably influence the critical velocity of a grass slope. In the following part, verification of the cumulative overload method is made with the test results achieved in Hai Hau – Nam Dinh.

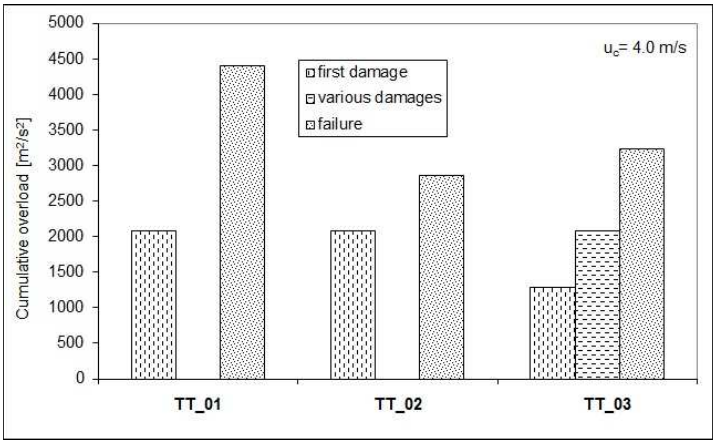

Figure 8. Comparison of cumulative overloads for various damage criteria, mixture of Bermuda and Vetiver grass slope, u_c = 4.0 m/s, flow velocity $u = 4.0V^{0.2}$.

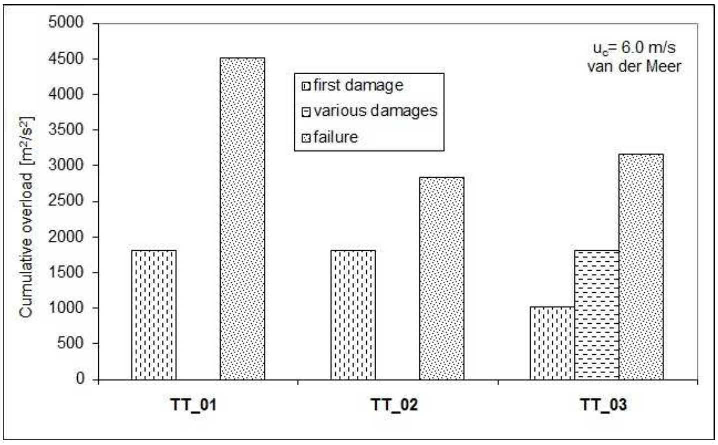

Figure 9. Comparison of cumulative overloads for various damage criteria, mixture of Bermuda and Vetiver grass slope, u_c = 6.0 m/s, flow velocity $u = 5.0V^{0.34}$.

Verification

In Nam Dinh, destructive tests were performed on a dike slope constructed with clay and covered with Bermuda grass. The dike crest level is at +5 m above MSL and 4.5 m wide, paved with concrete of 20 cm thick. The slope length is 10 m from crest to toe and the inclination is 1:3. The dike toe is about 10 m in width and is covered with Torpedo grass (*Panicum Repens*). Three slope sections, 4 m wide of each, were tested in order to investigate the influence of the variance of grass cover on wave overtopping resistance of the grassed slope.

At section TL_01, after 4 hours of 10, 20 and 40 l/s per m, the slope started to be eroded. After that 1 hour test with 70 l/s per m was performed and damages could be well recognised at various points such as on the slope and at the dike toe. Two more hours of 70 l/s per m resulted in a seriously damaged condition of the slope and the test was stopped. At test point TL_02, there was a Casuarina with diameter of 7 cm at the middle of the slope. After a couple of hours testing with 10 l/s per m, first damage started extending from an existing hole toward the Casuarina tree. After 2 more hours of 10 l/s per m and 30 minutes of 20 l/s per m, the Casuarina was swept away resulting a large hole on the dike slope. The last section in Nam Dinh, TL_03, which was poorly covered with a mixture of Bermuda grass and some small casuarinas (diameter of 1 cm), was first eroded after 4 hours of 10 and 20 l/s per m. Two more hours of 40 l/s per m showed that the slope was damaged at several points. The test was finished after another 1 hour of 40 l/s per m as the main hole became significantly large and could threaten the dike stability.

Due to the large variance in resistance against wave overtopping of the three test locations in Nam Dinh, the cumulative overload method was therefore verified by test results of TL_01, TL_02 and TL_03 separately. By doing trial and error, the “Failure” criterion with cumulative overload value of 3500 [m^2/s^2] was used to find the critical velocity that most seasonable for each slope section. The early failure of section TL_02, which was mainly due to the existence of a 7-cm-diameter Casuarina tree gives considerably lower value of critical velocity than those of sections TL_03 and TL_01, 2.1 m/s compared to 3.1 m/s and 3.7 m/s, respectively. The two criteria of First damage and Various damaged locations are far larger than corresponding values obtained at the Vechtdijk. This can be again explained by the difference in material of the two dike bodies, the Vechtdijk was a 100% sandy dike, covered with only 0.15 m of soil and grass whilst the Nam Dinh consisted a sand core and an outer clay layer of 80 to 100 cm thick.

A sensitivity analysis was made by applying the relation between flow velocity and overtopping wave volume Equation (2) in calculating the critical velocity. Much larger values were achieved to fulfil the Failure criterion, 5.2 m/s for TL_01, 2.5 m/s for TL_02 and 4.1 m/s for TL_03, with regard to 3.7 m/s, 2.1 m/s and 3.1 m/s when using Equation (1). Values of cumulative overloads computed for two velocity equations are depicted in Figures 10 and 11, respectively. With the exception of the First damage criterion, which is a constant verification parameter, the cumulative overloads of the first and the second damage criteria are smaller when the velocity equation of van der Meer is used.

All the calculation results made for 6 test locations in Nam Dinh and Thai Binh are tabulated in Table 3 giving the critical velocities applied for dike slopes which are constructed with clay, moderate or good quality, and mainly covered with Bermuda grass of at least 4 years old. It is hypothesized that the combination of soil structure and grass root system governs the critical velocity value. In case of a big tree or an eroded hole existing on the grass slope, damage can be rapidily stimulated and the failure stage will be quickly reached. As a result, critical velocity get much lower value, for example 2.1 m/s at a dike section in Nam Dinh. Within a dike stretch of 50 m in Nam Dinh, destructive tests showed that resistance of grass slope against wave overtopping varied considerably or in other words the critical velocity was not consistant along the dike stretch. The length effect on erosion resistance of a grass slope therefore should be investigated in future research.

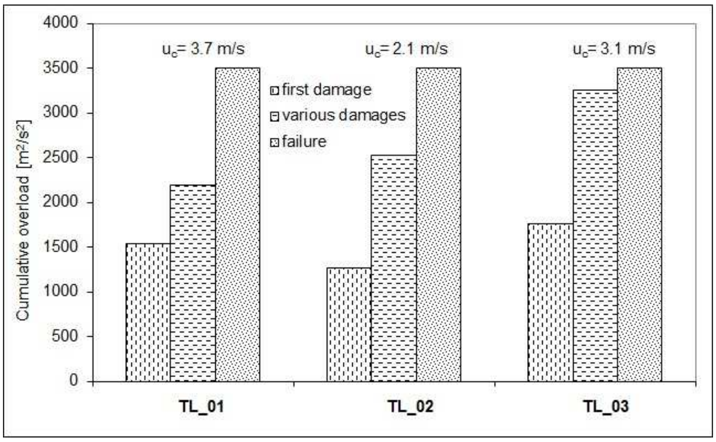

Figure 10. Comparison of cumulative overloads for various damage criteria, Bermuda grass slopes, flow velocity $u = 4.0V^{0.2}$ **.**

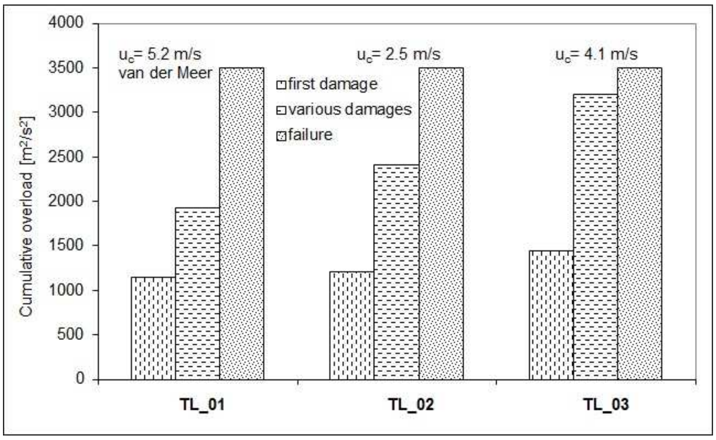

Figure 11. Comparison of cumulative overloads for various damage criteria, Bermuda grass slopes, flow velocity $u = 5.0V^{0.34}$ **.**

Table 3. Cumulative overloads for various damage criteria of grassed dike slopes, [m^2/s^2]

	$u = 4.0V^{0.2}$			$u = 5.0V^{0.34}$, van der Meer		
Section	u_c [m/s]	First	Various	u_c [m/s]	First	Various
TL_01	3.7	1533	2189	5.2	1141	1928
TL_02	2.1	1259	2518	2.5	1205	2409
TL_03	3.1	1758	3251	4.1	1440	3206
TT_01 TT_02 TT_03	4.0	1812	2076	6.0	1539	1802

CONCLUSIONS AND FUTURE RESEARCH

The cumulative overload method (Van der Meer et al., 2010) was applied to destructive tests on Bermuda grass slopes in Nam Dinh and mixed grass slopes in Thai Binh. Depending on the quality of the grass slope, the critical velocity could vary from 2.1 to 4.0 m/s resulting the cumulative overload of 3500 m^2/s^2 for the Failure criterion.

To comprehensively estimate the critical velocity for different grass slopes, it is recommended to investigate in depth the specifications of soil and grass at slope sections which were tested with the Simulator and of course more destructive tests are highly encouraged.

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