Wave Overtopping Simulator Tests on Sea Dikes in Viet Nam

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Abstract

Little is known about the strength and stability of the landward-side slopes of the sea dikes in the north of Viet Nam under wave overtopping attack. In the past, the strength of a grass-covered slope could only be quantified by real storm surges and by evaluating its post-storm condition. Some grass-covered dike slopes were tested by the wave overtopping simulator in 2009 and 2010. The simulator is a device that can generate wave overtopping flows on the dike crest and the dike slope. The paper describes the simulator and presents the test results. The tested grass covers could withstand wave overtopping rates varying from 20 to more than 100 l/s per metre of dike length. Damage usually started at existing bare spots, at the transition between steep part and horizontal dike toe, at the transition between different materials, and around objects (e.g., big trees) on the slope. These features reduce the strength of the grass covers and therefore should be avoided on dike slopes.

1 Introduction

In the north of Viet Nam, the sea dike system is clearly defined along the coastline of Quang Ninh, Hai Phong, Thai Binh, Nam Dinh and Ninh Binh provinces and has a total length of more than 700 km. The sea dike system was built with construction experience accumulated over centuries. The fundamental function of this system is to protect agricultural land from sea flooding and to prevent salt water intruding. In principle, a dike is constructed of a body of soil, an armoured seaward slope and crest, and a grass-covered landward-side slope. In general, dike crests are insufficiently high to prevent wave overtopping during storm surges or high tide. Damage induced by wave overtopping on the crests and landward-side slopes have caused a large number of sea dike failures. For example, overtopping was estimated to contribute up to 46% to the total failure probability of a sea dike in Nam Dinh province [Mai van, 2010].

To date, little is known about the strength and stability of the landward-side slopes of the present Vietnamese sea dikes under the impact of wave overtopping. Le et al. [2008] estimated that overtopping discharges at the sea dikes could vary roughly between 30 and 300 l/s per meter of dike length. According to the sea dike design guidelines currently applied in Viet Nam, a discharge of 10 l/s per m is accepted on the landward-side slope which is covered with good grass. In fact, the strength of a grass-covered slope can only be quantified by real storm surges and by evaluating the post-storm condition of the structure. Further, due to difficulties in performing observation and measurement during storm surges, it is almost impossible to investigate the damage process of a grass-covered slope. The critical rate of wave overtopping at sea dikes remains an issue that needs to be studied further.

Basic processes in coastal engineering are usually studied by using numerical and/ or physical models depending on which process is investigated. There are two main concerns: first, the available theory describing the process and the corresponding solutions; and second, whether it is possible to physically model the process.

The phenomenon of wave overtopping on coastal defences has been studied intensively for decades using physical models. On the basis of a large number of physical experiments, formulae have been established to characterise the phenomenon such as mean discharge, probability of overtopping, volume of a single overtopping event and distribution of overtopping waves during a storm surge [EurOtop, 2007, Schüttrumpf and Oumeraci, 2005]. However, the effects that overtopping waves have on landward-side grass-covered slopes are not comprehensively understood. On the one hand, that is mainly due to the fact that these effects cannot be studied in a small wave flume as it is impossible to scale down the properties of soil and grass. On the other hand, if it is possible to build up a prototype dike cross-section in a large wave flume, the grass cover needs one or two years to get mature and be suitable for testing. Besides, only one type of grass cover can be tested for each cross-section. To address this issue, a device that can simulate wave overtopping tongues on real dikes was developed in the Netherlands [van der Meer et al., 2006, van der Meer, 2007, van der Meer et al., 2008].

The Wave Overtopping Simulator was used to test the strength of various grass-covered slopes of sea dikes and river dikes in the Netherlands and Belgium between 2007 and 2011. These tests revealed that a grass cover could withstand a widely varying overtopping rate in the order of 10 l/s per metre of dike length [van der Meer et al., 2009]. Damage was observed to start at weak areas of the grass-covered slopes such as the transition between the steep part and horizontal dike toe, and around obstacles, such as a big tree or a staircase [Steendam et al., 2010]. The erosional resistance against wave overtopping of a grass cover is mainly determined by the root system rather than the soil characteristics [Steendam et al., 2008].

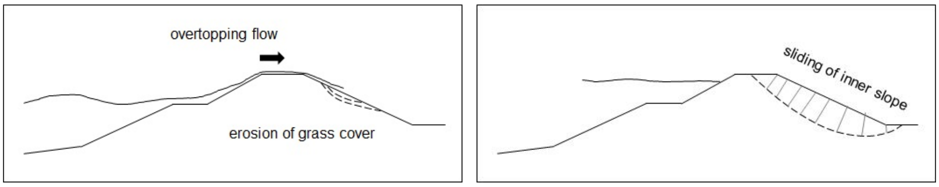
In the north of Viet Nam, the sea dikes are different in cross-sections, material components and grass species compared to those either in the Netherlands or in Belgium. It is not feasible to interpret and apply the findings obtained after the Dutch and Belgian tests to the sea dikes in the north of Viet Nam. Therefore, testing sea dikes with the simulator is strongly encouraged in Viet Nam. In late 2008, the original design of the simulator was adjusted and improved to make the second machine in Viet Nam. Since 2009, this new simulator have been utilised to test the strength of several grass-covered dike slopes in Hai Phong, Thai Binh and Nam Dinh provinces. The performance of the grass-covered dike slopes under wave overtopping attack was observed and investigated in order to understand and improve the present sea dike structures.

The results of the Vietnamese tests are presented in the paper. After the introduction, the operation principle and design of the simulator are given. Test sections and experimental conditions are described in the third section. Main test results are introduced in the fourth section. The formation and development of erosion induced by overtopping flows are discussed in the fifth section. Finally, conclusions and recommendations are given.

2 Wave Overtopping Simulator

2.1 Failure mechanisms due to wave overtopping

Wave overtopping may damage the crest and the landward slope of a sea dike covered with grass. In principle, two different mechanisms can be distinguished (see Figure 1). The first one is fast overtopping flow, which can damage the grass cover on the crest and the landward slope. If initial damage or erosion occurs, it can extend to the material layers underneath and may possibly lead to dike breaching. The second mechanism mainly occurs on steep slopes (especially between 1:1.5 and 1:2.0) due to water infiltration and sliding. This sliding may directly cause dike collapse. However, it is not likely to be due to wave overtopping as such, but rather due to large quantities of water infiltrating the dike body. This process may be aggravated by heavy rainfall. It is also possible for such failures to take place on slopes which are gentler than 1:3.



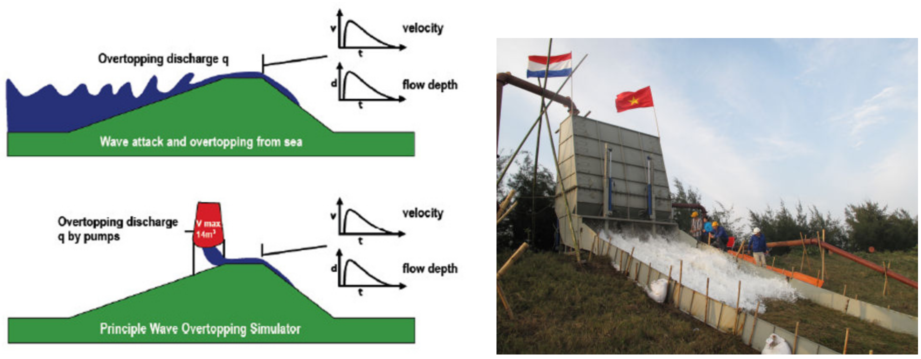
(a) Erosion by wave overtopping (b) Macro instability

Figure 1: Failure mechanisms of landward slopes.

In the present study, damage is regarded as an erosion process induced by overtopping flow. The overtopping flows are considered the load and the resistance against the flow loads is considered the strength of the grass cover. The Wave Overtopping Simulator was used to simulate the fast wave overtopping on real sea dikes to increase insights into erosional resistance against wave overtopping of different grass-covered slopes at several sea dike stretches. The simulated process was limited to the initial stage where grass cover was eroded to expose the lower material layer.

2.2 Operation principle and design

The Simulator is a water reservoir which is easy to transport from one place to another and quickly assembled or dismantled. When working, the simulator is continuously filled with a certain and constant discharge of water and is emptied at predefined moments through two butterfly valves at the bottom. The released water volumes simulate (generate) the overtopping wave tongues on the dike crest and then on the landward slope. The underlying principle is that it is not necessary to simulate the entire overtopping wave but only the water tongue on the dike crest and then the landward slope. Figure 2 illustrates the principle of the simulator and shows how it releases water on a grass slope. As long as the velocity and the depth of the released flow are similar to that which exists in reality on the dike crest, the flow behaviour on the landward slope will then automatically follow. The theoretical background and design of the simulator were described in van der Meer [2007].



(a) Operation principle [van der Meer, 2007] (b) Actual performance

Figure 2: Wave Overtopping Simulator.

The Vietnamese simulator is 4 m wide (along the dike stretch), 2 m thick and 5.5 m high giving a maximum unit volume of 5.5 m^3 per m of width and a total volume of 22 m^3. With this dimension a mean wave overtopping discharge of 100 l/s per m can be simulated. The machine is divided into two parts for convenience of transporting. The open width of the butterfly valve is 0.8 m giving better simulation of the water overtopping on the dike crest. The hydraulic pump opening and closing the valves is attached to the machine body. The vertical position of the simulator can be adjusted by six hydraulic legs. Two pumps with a respectively capacity of 22 and 55 kW respectively were used to fill the Simulator. Last but not least, a 250 kVA generator supplied power to all devices and equipments deployed during the tests.

3 Test sections and test scenarios

3.1 Description of test sections

In 2009 and 2010, tests with the simulator were performed on two real dike stretches in the north of Viet Nam. Positions were selected to satisfy operational and test requirements. Operation requires that heavy trucks (20 tons) and a 25 ton crane can approach the site easily and safely. A crest at least 4 m wide is required for positioning all equipments such as the simulator, the generator and the two pumps. The selected slope has to be covered partly or entirely with grass. A water source, either a canal or a pond close to the dike, is necessary to supply water for testing. A volume of roughly 9000 m^3 is estimated sufficient for testing in 4 to 6 hours with a discharge of up to 100 l/s per m. The two tested sites are described in the following paragraphs.

The first was in Nam Dinh province, where Thinh Long dike was constructed of a sand core and an outer layer of clay. The dike crest level is at +5 m above Mean Sea Level (MSL) and 4.5 m wide, paved with 20 cm thick concrete. The dike toe was about 10 m long and was covered with Ray grass (*Panicum Repens*). The 1:3-inclination slope was 10 m long, and was covered with mainly Bermuda grass (*Cynodon Dactylon*), sometimes in combination with Casuarina trees. Three sections were selected to reflect different slope characteristics and quality: TL1 was a regular slope covered with good grass, TL2 had a big Casuarina tree in the middle, and TL3 had been eroded at several points before testing. Water was pumped from a brackish water canal parallel to the dike toe. The Thinh Long dike cross-section is graphically illustrated in Figure 3.

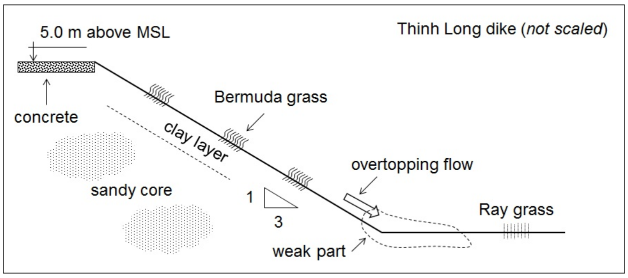


Figure 3: Cross-section of the Thinh Long sea dike.

The second site was on a estuary dike in Thai Tho commune, Thai Thuy district, Thai Binh province. A combination of Bermuda grass and Vetiver grass (*Vetiver Zizanioides*) on the riverside slope was tested at three positions: TT1, TT2 and TT3. The dike body was constructed of good clay, the 1:3 slope was reinforced with concrete frames from crest to toe. These sections were chosen to have different concrete beam configurations and grass quality. The horizontal berm was regularly covered with a dense sward of Ray grass. Water was pumped from Tra Ly river. A schematization of Thai

Tho dike is given in Figure 4. A brief description of all slope sections is given in Table 1.

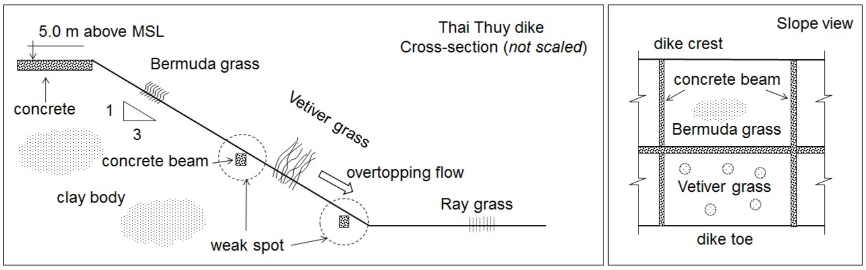


Figure 4: Schematization of Thai Tho sea dike.

Table 1: Description of tested slope sections.

Section	Length	Specifications	Grass age
TL1	10.0 m	regular slope, good cover of Bermuda, moderate clay;	Bermuda: 4 years
TL2	10.0 m	irregular slope with some small holes, poor mixture of grass species, a 7-cm-diameter Casuarina tree, moderate clay;	
TL3	9.5 m	relatively regular slope, very poor cover of grass around dike toe (2 m), moderate clay;	
TT1	9.0 m	regular slope, good cover of Bermuda grass + Vetiver grass, good clay, horizontal concrete beam;	Bermuda: 5 years, Vetiver: 6 months
TT2	9.0 m	regular slope, poor cover of Bermuda grass + Vetiver grass, good clay, horizontal and vertical concrete beams;	
TT3	9.0 m	regular slope, poor cover of Bermuda grass + Vetiver grass, good clay, horizontal and vertical concrete beams;	

3.2 Test scenarios

A wave condition was selected to represent the storm characteristics of the northern coast of Viet Nam. All of the destructive tests with the simulator were conducted with a wave height H_{m0} of 1.5 m and a peak period T_p of 6 s. The seaward-side slope of every dike was assumed to have a $\tan\alpha$ of 1:4. Depending on the strength of grass covers, different overtopping discharges were used, varying from 10 to 120 l/s per m. Each mean discharge characterising a storm was simulated for 4 hours. The simulated duration was reduced if the grass cover was already seriously damaged.

Each simulated storm is a distribution of overtopping volumes which is computed with the above wave condition and a given discharge. The procedure and formulae of the computation is given in EurOtop [2007]. In Figure 5, the vertical axis gives the overtopping volume, V, while the horizontal axis gives the number of waves, N_w, in ascending order. In reality, wave overtopping is a random process and for that reason, the volume order depicted in Figure 5 is randomized to control the simulator.

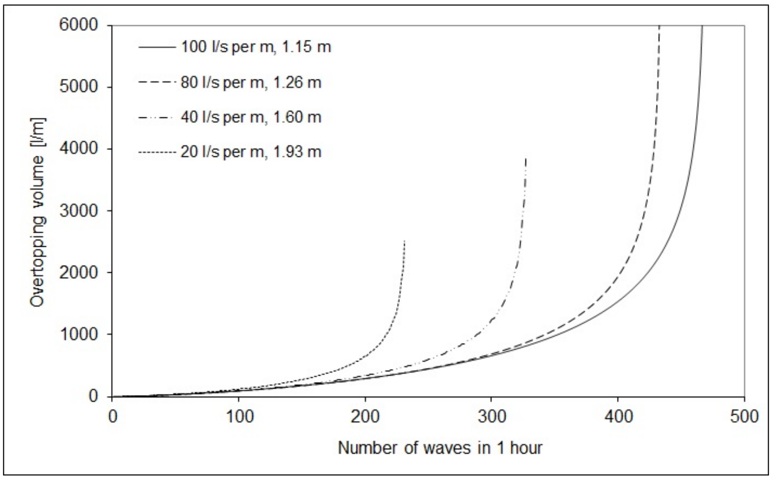


Figure 5: Distributions of overtopping volumes with different values of mean discharge.

Overtopping parameters are given in Table 2 with each discharge associated with corresponding durations applied at test sections. Note that at section TT1, tests were conducted during the high tide, and the dike toe was always submerged in water 10 to 20 cm deep. This water buffer was predicted to reduce the flow impact on the dike toe. At the other sections, water was free to flow over the dike toe.

3.3 Experimental procedure

The simulator was positioned on the dike crest to release water to the grass-covered slope under investigation. Two 50 cm high side walls were erected running from the simulator bottom gate to the dike toe in order to guide the overtopping flow (see Figure 2). A test with a certain discharge was paused after every hour to investigate the condition of the slope section by measuring cross-profiles and taking pictures. The experimental results at

Table 2: Wave overtopping parameters and test durations

Overtopping papameters	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	492
Maximum overtopping volume V_{max} (l/m)	1330	1900	2860	4120	4520	5300	6060
Test section	**Duration (hours : minutes)**						
Thinh Long TL1	4 h	4 h	4 h	3h			
Thinh Long TL2	4 h	1h49m					
Thinh Long TL3	4 h	4 h	2h20m				
Thai Tho TT1		4 h	4 h		4 h	4 h	
Thai Tho TT2		4 h	4 h		4 h		1 h
Thai Tho TT3		4 h	4 h		4 h	2 h	

the dike stretches Thinh Long and Thai Thuy are briefly described in the next section and more details can be found in Le [2011].

4 Main test results

4.1 Thinh Long Dike

At the section TL1, the slope started to be eroded after three 4 hour discharges of 10, 20 and then 40 l/s per m. After that, 1 hour of 70 l/s per m was applied and damage was clearly recognised at various points on the steep part and at the toe. Testing two more hours with 70 l/s per m seriously damaged the grass cover, and the test was stopped. Figure 6 compares the condition of grass cover before and after testing at the TL1 section. Figure 7 shows how the slope profile changed under the impact of overtopping flow. The profile was measured parallel to the left side wall (facing the simulator gate) with a distance of a = 2.5m. The vertical axis gives the distance from the Sea Water Level (SWL) in centimetres and the horizontal axis gives the distance from the crest edge where the grass cover starts in metres.

At section Thinh Long TL2, there was a Casuarina tree with a trunk diameter of 7 cm in the middle of the slope. After a couple of hours testing

(a) Before testing (b) After testing

Figure 6: Grass cover at Thinh Long TL1 section, maximum applied discharge q_{max} = 70 l/s per m.

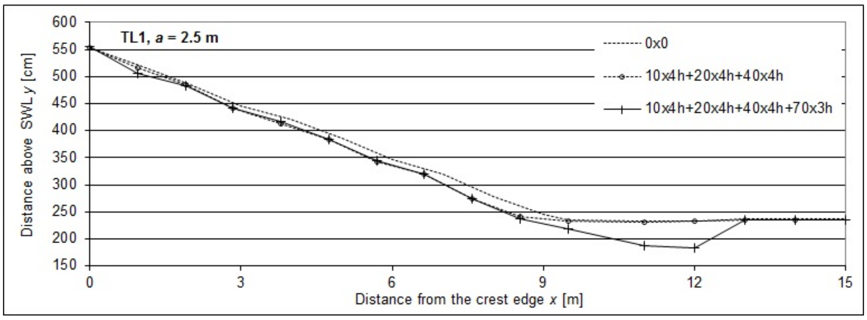


Figure 7: Changes of the slope profile induced by overtopping flow, distance from the left side wall a = 2.5 m, section Thinh Long TL1. 0x0 is the initial profile; 10x4h+20x4h+40x4h is the profile measured after 4 hours of 10, 20 and 40 l/s per m each.

with 10 l/s per m, the first damage extended from an existing hole towards the tree. After 2 more hours of 10 l/s per m and 30 minutes of 20 l/s per m, the tree was swept away, thus resulting in a large hole with a length of 3 m along the slope and a depth of about 1 m, as can be seen in Figure 8. The change of the slope profile in time measured 2.0 m away from the left side wall is depicted in Figure 9.

The third section TL3, which was poorly covered with a combination of Bermuda grass and some small Casuarina trees (trunk diameter of 1 cm), was first eroded after 4 hours of 10 and 20 l/s per m each. The slope was damaged at several points after 2 more hours of 40 l/s per m. The test finished after another hour of 40 l/s per m when the main hole became sufficiently large with a length of 5 m and a depth of 1 m, threatening the

(a) Before testing (b) After testing

Figure 8: Grass cover at Thinh Long TL2 section, maximum applied discharge $q_{max} = 20$ l/s per m.

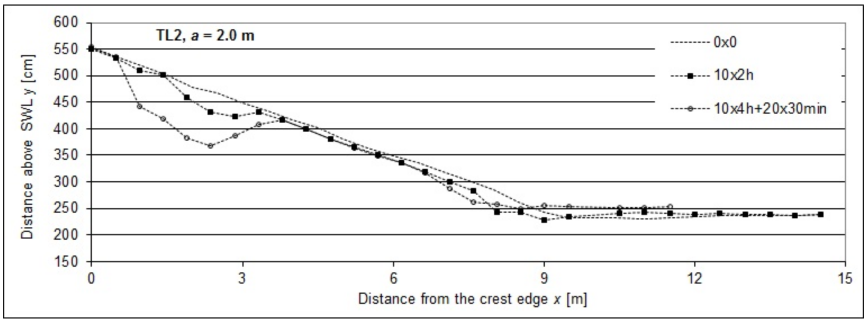


Figure 9: Changes of the slope profile induced by overtopping flow, distance to the left side wall $a = 2.0$ m, section Thinh Long TL2. 0x0 is the initial profile; 10x4h+20x30min is the profile measured after 4 hours of 10 l/s per m and 30 minutes of 20 l/s per m.

slope stability. The initial and final condition of the grass cover are shown in Figure 10, and the development in time of the profile at $a = 1.5$ m is given in Figure 11.

4.2 Thai Tho Dike

At section Thai Tho TT1, Bermuda grass was dominant while Vetiver clumps were scattered. The first damage took place above the horizontal concrete beam after three 4 hour tests of 20, 40 and 80 l/s per m. The slope failed after that 4 hours of 100 l/s per m. The initial and final condition of the grass cover are shown in Figure 12. Figure 13 illustrates the profile development in time at a distance of $a = 3.0$ m from the left side wall.

Section Thai Tho TT2 showed a similar strength to TT1, as it was first

(a) Before testing (b) After testing

Figure 10: Grass cover at Thinh Long TL3 section, maximum applied discharge q_{max} = 40 l/s per m.

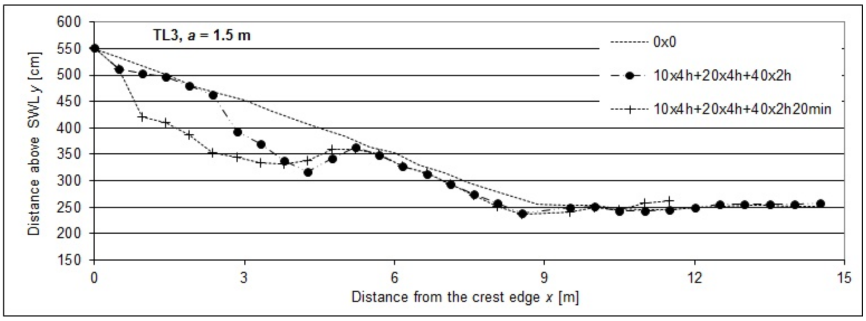


Figure 11: Changes of the slope profile induced by overtopping flow, distance to the left side wall a = 1.5 m, section Thinh Long TL3. 0x0 is the initial profile; 10x4h+20x4h+40x2h20min is the profile measured after 4 hours of 10 and 20 l/s per m each, and 2 hours and 30 minutes of 40 l/s per m.

damaged after 4 hours of 20, 4 hours of 40 and 4 hours of 80 l/s per m. One hour of 120 l/s per m was then applied, thus resulting in the slope failure. As shown in Figure 14, there was a hole under the horizontal concrete beam after testing. Repair to this kind of erosion is technically not easy, because it is difficult to compact soil under the beam. The slope profile with the deepest hole after testing is presented in Figure 15.

The third section TT3 showed first erosion after 4 hours of 20 and then 40 l/s per m, and 2 hours of 80 l/s per m. Erosion was observed at various points after 2 more hours of 80 l/s per m. The section failed after 2 more hours testing with 100 l/s per m. Damage extended in the flow direction creating a hole 3 m long by 1 m wide (see Figure 16). Figure 17 compares the slope profiles on both sides of the concrete beam.

(a) Before testing (b) After testing

Figure 12: Grass cover at Thai Tho TT1 section, maximum applied discharge q_{max} = 100 l/s per m.

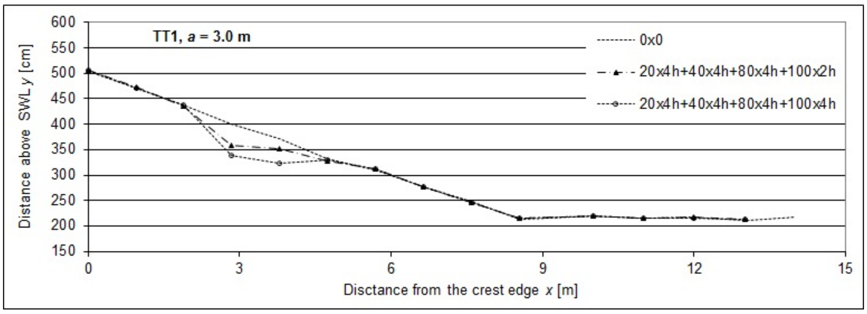


Figure 13: Changes of the slope profile induced by overtopping flow, distance to the left side wall a = 3.0 m, section Thai Tho TT1. 0x0 is the initial profile; 20x4h+40x4h+80x4h+100x4h is the profile measured after 4 hours of 20, 40, 80 and 100 l/s per m each.

There was always a water layer of 10 to 20 cm thick at the TT1 dike toe in order to simulate the scenario of a flooded landward-side area. At sections TT2 and TT3, water was free to flow over the dike toe. Damage took place at all three toes, but without any considerable difference. Configuration of the concrete frames was similar at TT2 and TT3 with both vertical and horizontal beams, but different from TT1 where there was only the horizontal beam. The final result at these sections were relatively similar as damage concentrated in the areas around the horizontal beam.

4.3 Wave overtopping discharges

In general, erosion on a grass-covered slope did not develop gradually under overtopping flow attack after being created. Depending on the specifications

(a) Before testing (b) After testing

Figure 14: Grass cover at Thai Tho TT2 section, maximum applied discharge q_{max} = 120 l/s per m.

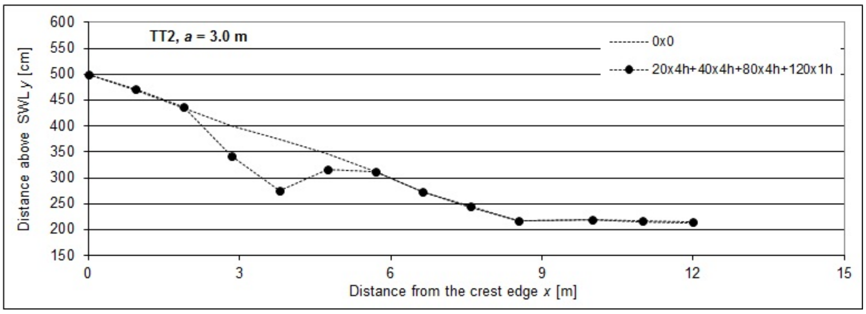


Figure 15: Changes of the slope profile induced by overtopping flow, distance to the left side wall a = 3.0 m, section Thai Tho TT2. 0x0 is the initial profile; 20x4h+40x4h+80x4h+120x1h is the profile measured after 4 hours of 20, 40 and 80 l/s per m each and 1 hour of 120 l/s per m.

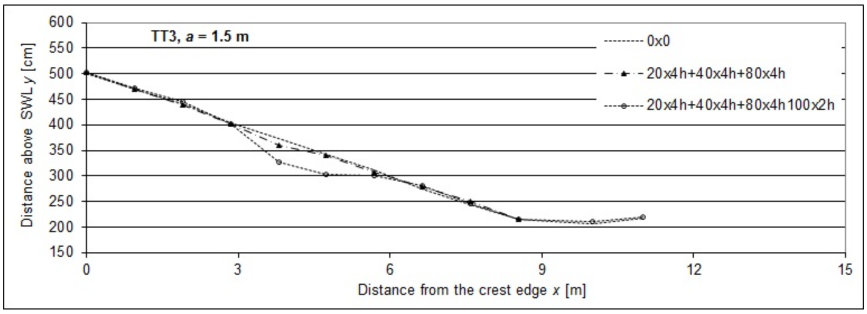
of each section, erosion would rapidly extend under a certain discharge; before that, little change was observed. The eroded hole at Thinh Long TL1 section enlarged suddenly during the second hour of 70 l/s per m. Damage gained 60 % of its final size during 30 minutes applying 20 l/s per m at TL2 section. Similarly, erosion of TL3 extended dramatically within the second hour testing with 40 l/s per m. Discharges less than 80 l/s per m did not erode the slopes at sections Thai Tho TT1, TT2 and TT3. Testing further with 80 l/s per m and larger rates, damage started and then developed rapidly.

Thai Tho dike stretch was homogeneously constructed of good clay. Even though the grass cover was different from section to section, the maximum discharge was relatively consistent, 100 l/s per m at TT1 and TT3, and

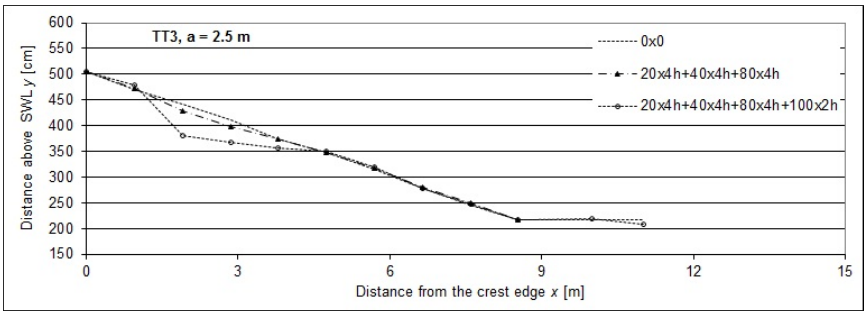
(a) Before testing

(b) After testing

Figure 16: Grass cover at Thai Tho TT3 section, maximum applied discharge q_{max} = 100 l/s per m.



(a) Distance to the left side wall a = 1.5 m



(b) Distance to the left side wall a = 2.5 m

Figure 17: Changes of the slope profiles induced by overtopping flow, section Thai Tho TT3. 0x0 is the initial profile; 20x4h+40x4h+80x4h+1002h is the profile measured after 4 hours of 20, 40 and 80 l/s per m each and 2 hour of 100 l/s per m.

120 l/s per m at TT3. On the contrary, test replications on Thinh Long dike revealed that grass cover strength could vary considerably along the stretch. The maximum discharge was up to 70 l/s per m at TL1 slope,

which was constructed of moderate quality clay with a thickness of 100 cm and covered with four year old Bermuda grass. At TL2, the combination between the poor cover of mat grass (e.g., Bermuda and Crabgrass) and the 7-cm-diameter Casuarina tree on a sandy clay layer of 80 cm thick could withstand an overtopping rate of 20 l/s per m. Section TL3, which was 80 to 85 cm of moderate quality clay, protected with a mix of mat grass and some small Casuarina trees, failed after more than 2 hours of 40 l/s per m. At Thinh Long, variation in maximum overtopping discharge is up to 3.5 times along a dike stretch of about 50 m long. Therefore, we can presume that a larger degree of uncertainty can be expected for a length of some kilometres.

According to the present standards of safety applied in some developed countries, tolerable discharge on a grass slope is in order of litres per second per metre of dike length. For example, EurOtop [2007] suggests mean wave overtopping discharges varying between 1 and 10 l/s per m. Experimental results in Viet Nam show that grass covers are able to withstand certain overtopping rates that are considerably higher than the currently recommended values. This finding is comparable to the results in the Netherlands and in Belgium [Steendam et al., 2010, van der Meer et al., 2009]. However, the simulator tests are limited to only two different types of slope, it is not reasonable to conclude or recommend the tolerable discharges on the grass-covered slopes of Vietnamese sea dikes. More tests will evaluate more properly the potential strength of the grass cover in protecting slopes, thus resulting in better guidelines on sea dikes design.

5 Damage formations

Section TL1 was covered by only one species of grass, Bermuda. A mix of different grass species such as Bermuda and Carpet grass (*Axonopus compressus*) was found at TL2 and TL3. Additionally, there were some Casuarina trees with different trunk diameters at these sections. Sections TT1, TT2 and TT3 were protected with a mix of Bermuda grass and Vetiver grass. Bermuda grass and Carpet grass form a continuous mat covering the slope surface, while Vetiver grass grows in separate clumps scattered across the dike slope.

A grass-covered slope is considered to be damaged when one or some aggregates of soil particles including sward and root are torn out of the slope surface and then moved away by overtopping flows. In other words, damage takes place when the grass cover is eroded at any point, even with small area and depth. Slope damage mostly started around Casuarina trees (obstacles) or at existing bare spots on slopes covered by mat grass (i.e., Bermuda and Carpet grass) such as TL1, TL2 and TL3. Areas among Vetiver clumps were usually eroded first at sections TT1, TT2 and TT3. Besides, these three sections were damaged more seriously around concrete beams. In general, damage often started at vulnerable areas as discussed further in the coming sections.

5.1 Transition between slope and horizontal dike toe

Section Thinh Long TL1 was eroded at the transition between the slope and the horizontal toe under a discharge of 40 l/s per m. At the transition area, Bermuda and Ray grass was poorer than on the higher part of the slope and the lower part of the toe (see Figure 18, right panel). Due to the thin cover of grass, soil was more directly exposed to overtopping flow, which was enhanced by the rough guidance in the flow course. Similarly, damage also took place at the sharp transitions from steep part to berm or toe in previous tests at Afsluitdijk and Vechtdijk in the Netherlands [Steendam et al., 2010].

(a) Rough guidance of flow (b) Thin grass cover around dike toe

Figure 18: Damage around the transition between the steep part and the horizontal toe at TL1.

The damage at TT3 dike toe is shown in Figure 19. When the top layer of grass sod (about 10 cm thick) was eroded, a concrete beam and a thin layer of cement mortar were found preventing grass roots from penetrating deeply the dike body. As a result, there were four separate elements with weak connections the grass sod, the mortar layer, the concrete beam and the soil body. Therefore, the grass sod and the mortar layer were easily eroded to reveal the body of soil underneath. The damage at the geometrical transition was possibly facilitated by the existence of different material layers.

(a) Horizontal concrete beam at dike toe (b) Cement mortar layer

Figure 19: Damage around the transition between the steep part and the horizontal toe at TT3.

5.2 Transition between different materials

Thai Tho dike slope was divided into separate cells by a system of concrete beams. The development of Bermuda and Vetiver grass covering these cell surfaces was not proportional. As can be seen in Figure 20, Vetiver clumps were cut off to expose a thin cover of Bermuda grass. The Vetiver grass overwhelmed the mat grass; in addition, grass was poorer and soil surface was lower (due to soil settlement) around the concrete beams than in the centre of the cells. Flow might concentrate among separate clumps due to the high shape of Vetiver, and around the concrete beams due to the uneven transition from soil to concrete. As a result, trenches were formed as depicted in Figure 20 and 16. Using different grass species and concrete frames might cause slope discontinuity, making it vulnerable to overtopping flow attack. Hewlett et al. [1987] recommended avoiding any feature that causes flow concentrations such as local gullies and low areas. However, more tests are required to provide sufficient evidence before drawing conclusion about the effects of Vetiver grass and concrete beams on the strength of the dike slopes.

(a) Thin cover of Bermuda (b) Erosion among Vetiver clumps

Figure 20: The grass-covered slope of Thai Tho dike.

5.3 Existing damage

It is hardly possible to prevent grass cover from being eroded or damaged by animal activities, dike inspection, and dike maintenance. At section TT3, erosion was first recognised at a mouse-hole as shown in Figure 21. Especially, small holes had been dug and then filled again to plant Casuarina trees at Thinh Long dike. These holes were quickly eroded by an overtopping rate of 10 l/s per m (see Figure 21) and then extended by larger discharges. However, small holes made by mice or moles did not initiate erosion under discharge of up to 50 l/s per m at Sint Jacobiparochie, the Netherlands [Steendam et al., 2008]. When the discharge was increased to 75 l/s per m, an area of 0.5 m^2 was lifted up below these spots. Accordingly, damage easily starts or extends from potentially weak points existing on a grass-covered dike slope, which should be regularly monitored and repaired.

5.4 Obstacles

At section TL2, damage started from an existing hole and then extended toward the 7-cm-trunk Casurina tree. Overtopping flow eroded and carried away soil aggregates held by roots, gradually reducing the connection between the tree and the slope. The anchoring force became weaker and weaker, finally resulting in the tree's collapse. The amount of surrounding

(a) Damage at a mouse-hole (b) Erosion around a Casuarina tree

Figure 21: Damage starts at eroded holes on grass-covered slopes.

soil associated with this collapse was more considerable than what could be swept away by a grass sod erosion because the larger root system of the Casuarina tree in both diameter and length. The large trunk also caused flow blockage, hence increasing force intensity. Figure 22 gives impressions of the flow and damage around the Casuarina tree at section TL2.

(a) Flow around the Casuarina tree (b) Damage extended to the Casuarina tree

Figure 22: Flow and damage around the 7-cm-trunk Casuarina tree, Thinh Long TL2 section.

6 Conclusions and recommendations

This paper has described the *in situ* tests at two dike stretches in the north of Viet Nam. For the first time, the strength of grass-covered sea dike slopes in Viet Nam was evaluated using the wave overtopping simulator which can generate simulated wave tongues on a real dike crest. The device was first developed in the Netherlands [van der Meer, 2007]; the original design was then improved to manufacture the Vietnamese version with a capacity of up to 100 l/s per m of dike length. The selected sections reflected various slope specifications and grass species.

Experimental results gave insights into the performance of grass covers under overtopping flow attack. It was revealed that a grass cover could withstand a discharge in the order of 10 l/s per m. However, more tests are needed to confirm this finding. Further studies, including simulator tests, are needed to better evaluate the strength of the grass-covered dike slopes. High sea dikes without any wave overtopping (i.e., zero discharge) are hardly achievable in developing countries like Vietnam due to budgetary constraints. Dikes could be lower and cheaper if certain overtopping rates are allowed corresponding to the strength of grass covers.

The simulator tests emphasises that damage often takes place at the transitions between slope and dike toe, the transitions between different materials, places with existing damage, and around obstacles on grass-covered slopes. A gentle connection between the slope and the dike toe apparently creates smoother flow.

Planting Bermuda grass, Carpet grass and Ray grass, which have rhizomes and stolons, will cover a slope surface evenly and continuously, thus resulting in fewer exposed spots. Regular and careful dike monitoring will help to recognise minor damage which needs to be repaired immediately to eliminate further erosion. Obstacles like trees, stones and staircases should be avoided because these can interrupt the continuity of the grass cover and partly block the flow.

To conclude, tests with the simulator provide new insights into the performance and strength of grass-covered dike slope and reveal its vulnerable areas under overtopping flow attack.

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