

WAVE OVERTOPPING TESTS TO DETERMINE TROPICAL GRASS SPECIES AND TOPSOILS FOR POLDER DIKES IN A TROPICAL COUNTRY

Jentsje van der Meer^{1, 2}, Gosse Jan Steendam³, Cesare A. Mosca⁴, Luca Bolatti Guzzo⁴, Koichi Takata⁴, Ng Say Cheong⁵, Chua Kok Eng⁵, Lionel Ang LJ⁵, Goh Pei Ling⁵, & Chua Wee Siang⁵, Chia Way Seng⁶, M. Karthikeyan⁶, Francis Yap SC⁶ and Vivek Govindasamy⁷

A dike or levee will protect a polder to build in a tropical country against coastal flooding. To ensure that the performance of the dike is in accordance with the safety standard, wave overtopping tests with a wave overtopping simulator have been performed on a mock-up dike. These wave overtopping tests will guide the selection of the grass species and topsoil for the grass cover of the landward side of the dike. The paper describes the design of a new dedicated wave overtopping simulator, the construction of the mock-up dike, the results of the eight tests on the mock-up dike and the critical velocities (strength indicator of the grass cover) established with the cumulative overload method.

Keywords: wave overtopping, wave overtopping simulator, grass cover, dike, levee

OBJECTIVES OF TESTING

A polder, a reclaimed land with land level below sea level is protected against coastal flooding by a dike, is being realised in Asia in a tropical climate. The crest level has been designed high enough to expect only little wave overtopping under very extreme conditions. To ensure the design of the polder dike is in accordance to the design requirements, wave overtopping tests were performed on a constructed mock-up dike or test dike at the project site. The test results would then guide the selection of grass type and topsoil for the actual dike.

The overall objective of the wave overtopping tests is to understand and determine the strength of individual combinations of grass and topsoil and provide a ranking of the combinations by strength. Combinations of selected grass species and topsoil were produced on the mock-up dike. The strength is determined by the resistance against loads of overtopping waves simulated with the wave overtopping simulator. The wave overtopping simulator simulated overtopping wave volumes at the crest of a dike based on a hypothetical storm with high water levels with a range of overtopping discharges for given wave heights. The results give a critical velocity (strength indicator) for each individual grass-soil combination. The analysis of the wave overtopping tests results provided a ranking of strength of individual grass-soil combinations and also provides an indicative on the strength of some transitions in the slope profile.

The objectives for the dike landward slope grass cover testing are as follows:

- a) To show the behaviour of the test plots at the design conditions;
- b) To get insight in strength of crest and landward slope for wave overtopping beyond and far beyond design conditions. These tests will show the safety beyond design conditions;
- c) To select the type of grass and topsoil as provided, based on the wave overtopping tests in combination with grass pull tests and root quality tests;
- d) Optimisation of transitions and other details. Standard cross sections and non-standard cross sections such as a ramp or road crossing that connects a road in the hinterland to the road on top of the dike were studied. Each cross section has different type of transitions such as the geometric transition where the slope gradient vary along the profile and the material transition, i.e. from road at the crest to grass slope. Field testing at full scale will identify the weaknesses of transitions and other details.

In general, the scope of the wave overtopping tests included the design and construction of a mock-up dike, construction/seeding and maintenance of the grass cover over a year, design and construction of a dedicated wave overtopping simulator, setting-up the simulator on the mock-up dike, performance of wave overtopping tests and analysis of all the results.

¹ Van der Meer Consulting, PO Box 11, 8490 AA Akkrum, the Netherlands, jm@vandermeerconsulting.nl

² IHE Delft, PO Box 3015, 2601 DA Delft, the Netherlands

³ Infram Hydren, Maarn, the Netherlands

⁴ Boskalis / Penta Ocean Joint Venture, Singapore

⁵ Housing & Development Board, Singapore

⁶ Surbana Jurong Consultants Pte Ltd, Singapore

⁷ National Parks Board, Singapore

This work was performed as a cooperation between BPJV (Boskalis/Penta Ocean Joint Venture), Infram Hydren and Van der Meer Consulting. From Infram Hydren Mr Gosse Jan Steendam was available as Grass Pull Specialist and from Van der Meer Consulting Professor Jentsje van der Meer acted as the Wave Overtopping Specialist. BPJV designed and constructed the mock-up dike with advice from both other companies, the client, advisors and consultants. This occurred between May 2018 and March 2020. In order to perform wave overtopping tests, a dedicated wave overtopping simulator was designed and constructed in the Netherlands by Van der Meer Consulting. It was transported to the project site in 40 feet container in January 2020. The wave overtopping tests were performed by a highly specialised team from Infram Hydren guided off-site by Prof. Van der Meer and Mr. Gosse Jan Steendam, on behalf of BPJV.

WAVE OVERTOPPING SIMULATION

Theory of wave overtopping

Wave overtopping has been described in EurOtop (2018) and is adopted in this wave overtopping test. Figure 1 shows the process of wave breaking, run-up and overtopping at a dike. Calculations that will be the input for the design of the wave overtopping simulator are performed up to aspect 4 in Figure 1. The wave overtopping simulator will simulate overtopping waves on aspect 5 in the graph, where the landward slope is the subject of the testing.

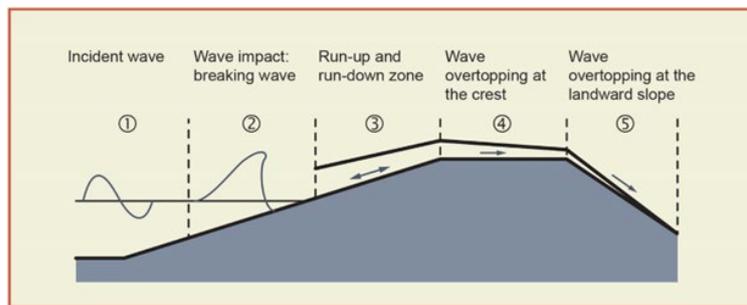


Figure 1. Wave breaking, run-up and overtopping at a dike. Original Fig. 4.32 in EurOtop (2018).

Overtopping calculations should lead to a distribution of overtopping wave volumes that should be simulated by the wave overtopping simulator in a certain period of time. The real execution of wave overtopping volumes will be in random order, but in total all the individual waves of a distribution will be simulated. The wave boundary conditions and dike geometry, extended with the required wave overtopping discharge and the test duration, give the input to the calculations.

EurOtop (2018) Equation 5.4 and 5.5 were used to calculate wave run-up and with Equation 5.56 the number of overtopping waves; Equations 5.12 and 5.13 were used to calculate the required freeboard for a given wave overtopping discharge; and Equations 5.52 – 5.54 were used to calculate the distribution of overtopping wave volumes for each test condition.

For the project the design conditions of the dike have been the basis to establish test conditions for the wave overtopping simulator. The seaward design of the dike slope and the crest are input for wave overtopping calculations and give the wave overtopping volumes and velocities that had to be simulated.

Wave overtopping conditions

A summary of design conditions had been provided by the client. The wave heights and periods vary, depending on the location of the dike and the return period. Wave overtopping will only occur for very extreme conditions and therefore the largest return periods were chosen to establish a test wave climate. The conditions for a 1000-year return period give wave heights H_{m0} between 0.9 m and 1.2 m and spectral wave periods $T_{m-1,0}$ of 3.0 s to 3.6 s. The conditions for a 100,000-year return period give wave heights H_{m0} between 1.2 m and 1.5 m and spectral wave periods $T_{m-1,0}$ of 3.6 s to 4.0 s, where the maximum wave height of 1.5 m at location 4 has a wave period of 3.9 s.

It is assumed that lower wave conditions represents small overtopping discharges of 1, 10, 50 l/s per m width and the most extreme wave conditions represents the largest 100 and 200 l/s per m width. This led to the following wave conditions that have been used to design the wave overtopping simulator as well as the conditions that were assumed to be present when performing the tests.

Adopted conditions for testing as well as for design of the wave overtopping simulator:

- Overtopping discharge 1, 10 and 50 l/s per m: $H_{m0} = 1.2$ m; $T_{m-1,0} = 3.2$ s
- Overtopping discharge 100 and 200 l/s per m: $H_{m0} = 1.5$ m; $T_{m-1,0} = 3.9$ s

The geometry of the seaward part of the dike and crest determine the wave overtopping in combination with the wave conditions. The seaward slope is 1:3 ($\cot\alpha = 3.0$) and the surface is considered as smooth, which might be a little conservative, leading to an influence factor for the roughness in overtopping calculations of $\gamma f = 1.0$.

Figure 2 gives the distributions of overtopping wave volumes for all test conditions. The first test condition of 1 l/s per m has only 400 overtopping waves and a maximum of only 500 l/m. The graph with solid lines shows the overtopping volumes that have been simulated and the 10 largest volumes of each overtopping rate were indicated with markers. The dashed line gives the theoretical lower part of the distributions, the horizontal lines represent the minimum volumes that can be simulated by the wave overtopping simulator, depending on the pump discharge rate (i.e. volume and time taken to fill the simulator). The distributions of overtopping wave volumes in Figure 2 have been randomly simulated during testing.

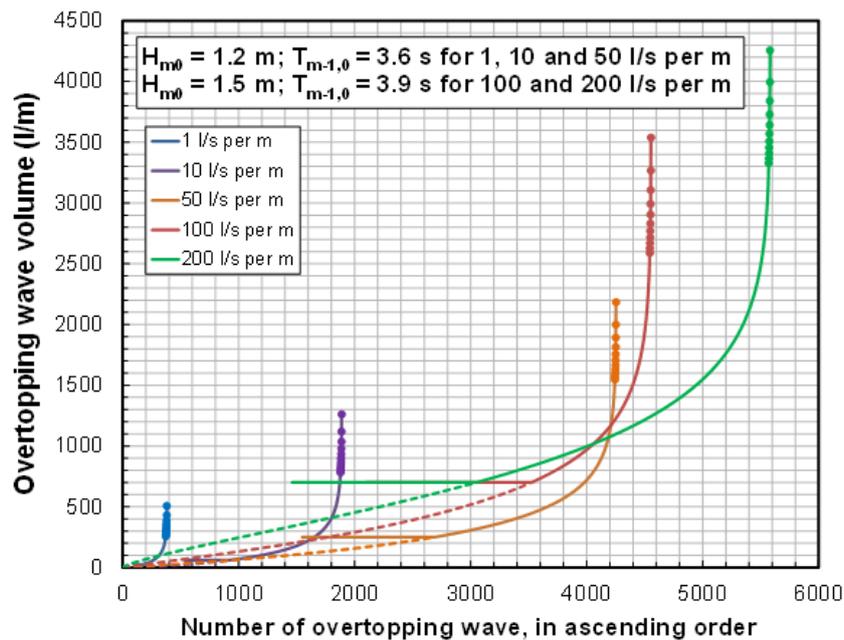


Figure 2. Distribution of overtopping wave volumes as simulated for all test conditions.

Method of cumulative overload

The tests on grass cover with the wave overtopping simulator in the Netherlands have resulted in a method that describes the strength of a grass cover as a function of the wave overtopping. References are Van der Meer (2017), Van der Meer *et al.* (2010, 2018), Hoffmans *et al.* (2018), Bijlard *et al.* (2016) and Steendam *et al.* (2010, 2013, 2014). The method is called the cumulative overload method. It considers the front velocity along the crest and landward slope of the dike for each overtopping wave volume with a strength indicator for the grass, the so-called critical velocity.

The idea is that small overtopping volumes generate small front velocities and that velocities below a certain threshold do not damage the grass cover. Larger overtopping wave volumes that generate larger front velocities, above this threshold, will contribute to damaging the grass cover. A larger threshold means a stronger grass cover, as it needs larger overtopping waves to damage it. This threshold is called the critical velocity of the grass cover. As every large overtopping wave with a front velocity above the threshold or critical velocity adds to damage, the contribution of each of these overtopping waves is added up. That is why it is called the cumulative overload method (cumulative = adding up and overload = larger than the threshold).

This cumulative overload is called D (m^2/s^2). It is assumed that the damage that may be done to the grass cover relates to the square root of the velocity, not to the velocity itself. This means that the basic relationship for the cumulative overload method is:

$$D = \sum_{i=1}^N (U_i^2 - U_c^2)$$

If the cumulative damage D adds up to a certain value, it describes the status of the damage. This may be broadly categorised into: initial damage (first erosion spot, for example), several open spots, and up to failure of the grass cover, where the topsoil and sometimes also the subsoil has been eroded to a certain depth. The testing has to show when a certain status of damage has been reached: the D -value is then known. With the overtopping waves that have been generated, all front velocities, U_i , are known. Then the strength of the grass cover, U_c , can be calculated.

In reality it may be a little more complicated. Overtopping waves may increase in front velocity if they run down the slope (due to gravity). This means that the U_i may increase along the landward slope. One needs to use the correct front velocity at the location of the damage. It may also be possible that the slope varies, for example at the toe, where the slope becomes horizontal. In that case there may be an increased influence of the force (the front velocity), which is described by a factor on this front velocity U_i . It is also possible that due to objects, transitions or use of the grass, the grass has a lower strength than the plain grass cover. That can also be taken into account by a factor, but now on the critical velocity U_c .

The complete cumulative overload method is then described as follows:

$$D = \sum_{i=1}^N (\alpha_1 U_i^2 - \alpha_2 U_c^2) \quad \text{for } \alpha_1 U_i^2 > \alpha_2 U_c^2 \quad [\text{m}^2/\text{s}^2]$$

with:

- D = cumulative overload [m^2/s^2]
- N = number of overtopping waves [-]
- i = number of the overtopping wave [-]
- U_i = a characteristic value of the front velocity of the overtopping wave [m/s]
- U_c = critical velocity of the grass slope (=strength) [m/s]
- α_1 = influence factor on the velocity U_i by transitions or obstacles [-]
- α_2 = influence factor on the critical velocity U_c by transitions or obstacles [-]

Small overtopping wave volumes with a front velocity smaller than the critical velocity of the grass cover do not add to the cumulative overload. It are the larger overtopping wave volumes that may lead to damage. The influence of transitions or obstacles can be taken into account by the influence factors α_1 and α_2 . These influence factors may increase the load or decrease the strength.

Damage development during testing of grass covers is often seen as a first initial damage (eroded spot), followed by several open spots and if the overtopping load is large enough, it may lead to failure of the grass cover. Sometimes this damage development is seen as a gradual process, but sometimes a grass slope does hardly show any damage and then it may fail quite quickly (for large wave overtopping). This means that the definition of initial damage and several open spots is quite uncertain and may fluctuate significantly. The cumulative overload method has mainly been focused on failure of the grass cover.

Dutch research led to the following values for cumulative overload:

- Initial damage $D = \Sigma(U_i^2 - U_c^2) = 1000 \text{ m}^2/\text{s}^2$
- Several open spots $D = \Sigma(U_i^2 - U_c^2) = 4000 \text{ m}^2/\text{s}^2$
- Failure $D = \Sigma(U_i^2 - U_c^2) = 7000 \text{ m}^2/\text{s}^2$

These cumulative overload values have also been used for the tests in a tropical climate in Asia. With the results from the tests the cumulative overload can be calculated, leading to a value of the critical velocity of the grass cover, U_c . These values are not known for tropical grass covers and will be a result of the testing. For Dutch conditions the following critical velocities were found for four categories of grass with topsoil:

- | | | |
|--|-------------------------|-----------------------------|
| • Well maintained grass on clay | $U_c = 8 \text{ m/s}$ | $\sigma = 1,0 \text{ m/s}$ |
| • Maintained grass, some open spots, on clay | $U_c = 6 \text{ m/s}$ | $\sigma = 0,75 \text{ m/s}$ |
| • Well maintained grass on sand | $U_c = 3.5 \text{ m/s}$ | $\sigma = 0,5 \text{ m/s}$ |
| • Bad coverage, no maintenance, poor soil | $U_c = 0 \text{ m/s}$ | $\sigma = 0 \text{ m/s}$ |

SET-UP OF THE TEST SITE

Construction of the Mock-up dike

In order to be able to perform tests, a mock-up dike has been constructed. The design started from May 2018 and the construction took approximately 6 months. Upon completion, the grass was seeded on the mock-up dike. After a year, to allow the grass to develop to a mature grass cover, the wave overtopping tests commenced.

The mock-up dike, covering an area of 61 m by 234 m, was constructed within the project site. The mock-up dike was sized to provide 8 test plots at a total length of 80 m. In total 6 test plots (plots 1-6) were to represent the dike with standard cross sections with different combination of the grass type and topsoil. The last two test plots 7 and 8 were the non-standard cross section, i.e. cross-section with a ramp.

Each test plot was 10 m wide, where 4 m in the middle was reserved for the wave overtopping tests. The other two sections of each 3 m wide were reserved for root density and quality tests and grass pull tests (Bijlard *et al.*, 2016).

A cross-section of the mock-up dike for test plots 1-6 is shown in Figure 3. The first three combinations had a 300 mm topsoil, given as the so-called CUGE'S Alternative Soil Mix. The next combinations had the HDB Standard Soil Mix. Two types of grass were seeded in three combinations: Bermuda Grass (Cynodon Dactylon), Manila Grass (Zoysia Matrella) and a combination of 50% Bermuda with 50% Manila grass. Table 1 gives an overall view of the 8 test combinations with top soil and grass cover. Test plots 7 and 8 had the HDB Standard Soil Mix with the 50% combination of Bermuda with Manila grass. Topsoils and grass types were specified by the HDB.

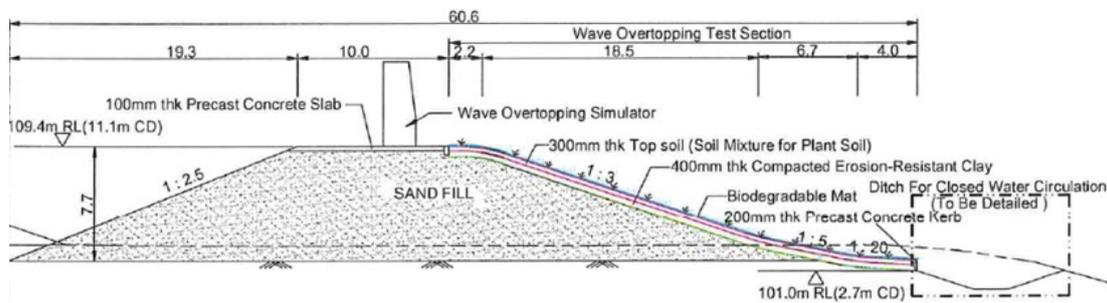


Figure 3. Cross-section of the mock-up dike for Test plots 1-6. The landward side (right) from the crest till toe has been constructed as designed for the actual dike.

Table 1. In total 8 test plots with different topsoils and grass types.		
Test Plot No.	Top Soil	Grass type
1	CUGE	Bermuda Grass – Cynodon Dactylon (50%) + Manila Grass – Zoysia Matrella (50%)
2	CUGE	Manila Grass – Zoysia Matrella
3	CUGE	Bermuda Grass – Cynodon Dactylon
4	HDB	Bermuda Grass – Cynodon Dactylon
5	HDB	Manila Grass – Zoysia Matrella
6	HDB	Bermuda Grass – Cynodon Dactylon (50%) + Manila Grass – Zoysia Matrella (50%)
7	HDB	Bermuda Grass – Cynodon Dactylon (50%) + Manila Grass – Zoysia Matrella (50%)
8	HDB	Bermuda Grass – Cynodon Dactylon (50%) + Manila Grass – Zoysia Matrella (50%)

Performance of tests

Figure 4 (left) gives an overall view of test plots 1-6 after half a year of seeding in September 2019. At that time the situation grass growth was already quite established and the first grass pull tests were performed after half a year of seeding.

The actual testing with the wave overtopping simulator started in March 2020, one year after seeding of the grass. The grass pull tests were also repeated. Due to the COVID-19 pandemic in March 2020, the testing did start, but was temporarily suspended after two tests on test plot 1 and 2. The tests for the remaining plots resumed in October 2020 and all the tests had been finished by November 2020. Figure 4 (right) shows an overall view of the test sections in March 2020, when testing test plot 2.



Figure 4. Overall view of Test plots 1-6, September 2019 (left). Overall view by drone of testing test plot 2. The tested Test plot 1 (brown grass) is on the left side and Test plots 3-5 on the right side.

DEDICATED DESIGN OF THE WAVE OVERTOPPING SIMULATOR

A dedicated design of the overtopping simulator was made to match the design conditions at the project site and beyond. Design calculations for the wave overtopping simulator, as shown in Figure 2, led to a minimum volume of the simulator of approximately 4 m³ per m. The simulator was 4 m wide, equal to the Dutch and Vietnamese simulators and had a volume of 4.3 m³ per m width, or 17.2 m³ in total.

The velocities of the overtopping wave volumes, close to the outflow of the wave overtopping simulator, were designed to be a little larger than those of the Dutch simulator. Based on the experience with the earlier designed wave overtopping simulators larger velocities can be achieved by:

- a more slender design;
- a shape with less contraction;
- one drawer type valve;
- less “free falling water” by opening the valve from the side of the transition section.

Figure 5 gives the theoretical cross-section of the new simulator. The cross-sectional width is 1 m and rectangular in shape. In order to guide the released water best, a drawer type valve is designed under an angle of about 45° and opens upwards. The height, from lowest point of valve up to the top, will be around 5 m, giving the total volume of 4.3 m³ per m width.

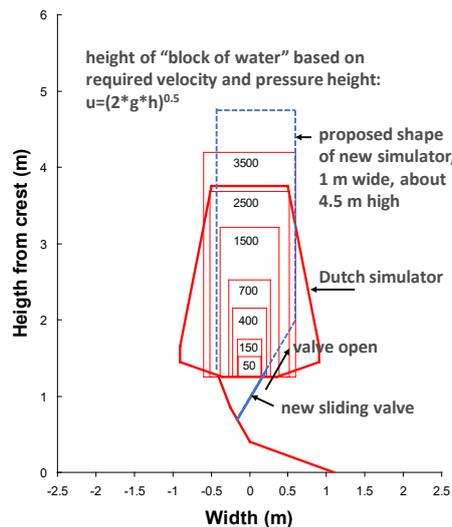


Figure 5. Cross-section of the new wave overtopping simulator.

The wave overtopping simulator was designed and constructed in the second half of 2019 and calibrated in December 2019 in the Netherlands. Figure 6 shows the set-up for this system test. Outflow velocities were measured and were according to expectations. The steering system was also tested and worked well. The simulator was transported in three pieces (the lower frame with valve, a middle box and an upper box) to the project site in 40 feet container in January 2020.

In February 2020, the test was set-up at the project site for test plot 1. The wave overtopping simulator was placed on a concrete crest with the outflow 1.5 m from the start of the grass at the

landward side of the crest, see Figure 7. Two pumps with a capacity of about 800 m³/hour were installed to extract seawater to the simulator via a pipeline as shown in Figure 7.



Figure 6. One of the first wave releases during the system tests, directly after fabrication.



Figure 7. The wave overtopping simulator in action, taken by drone. The pipeline for water supply is shown in the background behind the simulator.

RESULTS OF TESTING

Test plots 1 and 2 were tested up to 50 l/s per m due to COVID-19. These tests showed no erosion or loss of grass cover, but an overall superficial erosion of topsoil of a few centimetres. It was also noticed that at the test plots where a combination of 50% Bermuda grass with 50% Manila grass had been seeded, only Bermuda was present. The development from seeds of Bermuda grass was faster than for Manila grass. The plots with a combination of grass species could therefore be assumed as only Bermuda grass. It was also noted that in the two test plots with Manila, it is more prominent that other grass species entered, including some weeds.

Some of the test plots failed at some instance, a few withstood the whole test sequence up to 200 l/s per m of overtopping discharge. Figure 8 shows the final situation of test plot 3 after a little more than 1 hour with the last subtest of 200 l/s per m overtopping that is far beyond the design requirements. Superficial erosion of the topsoil led to small erosion holes and subsequently a large erosion hole where the subsoil had also eroded.

Similar processes were also observed in test plot 4. Superficial erosion of the topsoil led to larger erosion holes, as seen in Figure 9 after 50 l/s per m of overtopping. Although the topsoil has eroded, the grass is still maintained. Grass was only removed when all the topsoil had been eroded as shown in Figure 10.

The final damage at test plot 4 also occurred about 1 hour into the test with 200 l/s per m overtopping that is far beyond the design requirements. Refer to Figure 10. The topsoil, as well as the subsoil, had been eroded and the sand core eroded quickly. In addition, the mechanism of head-cut erosion was

present and can be noticed in Figure 10. In such a case, water infiltrates the clay above the hole and large lumps of clay fall into the erosion hole and are then taken by large overtopping waves. In such a way, a vertical front is present and this vertical front travels upwards to the crest.



Figure 8. Test plot 3. The outcome after 1 hour and 11 minutes with 200 l/s per m (a condition far beyond design requirements). The side wall was undermined and failed. Large lumps of subsoil were eroded.



Figure 9. Test plot 4. Initial erosion hole after 6 hours with 50 l/s per m. The topsoil is largely eroded with the grass still maintained.



Figure 10. Test plot 4. The final situation after terminating the test at 1 hour and 38 minutes with 200 l/s per m (a condition far beyond design requirements); left the large erosion hole with the mechanism of head cut erosion and right the whole slope seen from the toe.

Test plot 5 did not show major damage and survived the full sequence of testing as shown in Figure 11. The topsoil eroded less and seemed to be stiffer than at all other plots. Small erosion holes and an erosion hole near the crest at the transition from concrete crest to grass were detected. In most of the plots that kind of damage or erosion occurred, but it never led to deep erosion or failure at the crest.



Figure 11. Test plot 5. The slope at the crest after 200 l/s per m, with the erosion area directly behind the crest.

The Bermuda grass at test plot 6 had taken over Manila grass. However, the grass in test plot 6 had not yet been mowed to test the influence of long and not mowed grass on the erosion resistance. The grass was about 30-40 cm long with some individual grasses over 1 m in length. The grass acted as an armour to the topsoil, see Figure 12. There was little superficial erosion, but no erosion holes were detected. The pack of grass became thinner during testing, but it acted as an armour during the whole testing. Only some erosion was noticed at the transition from the concrete crest to grass as shown in Figure 12 but did not lead to failure.



Figure 12. Test plot 6. Long grass (30-40 cm). Final situation after 200 l/s per m discharge at the crest.

Test plot 7 had a ramp or road crossing in the mid-section of the slope, see Figure 13. The upper slope consisted of open pavers and bricks. A drain with precast concrete elements had been designed between the upper slope and the ramp, which was constructed in sand. Earlier tests had shown that erosion of sand may lead to early failure. Therefore, test plot 8 had been designed without a drain and pavers.

The overtopping waves eroded the topsoil from the open pavers on the upper slope and then also beneath the pavers. The waves could reach the sand underneath the drain and started to erode this sand. It undermined the precast drain and just after the start of the 100 l/s per m (a condition that is far beyond the design requirement) the drain collapsed, see Figure 14. Not only the drained had been undermined, but also quite a large part underneath the ramp or crossing road (the horizontal concrete plate at the top in Figure 14). At the time of this failure, the open pavers that were undermined were still present. They

acted as an arc without support of soil and it could be assumed that it was only a matter of time that this structure would also have collapsed.

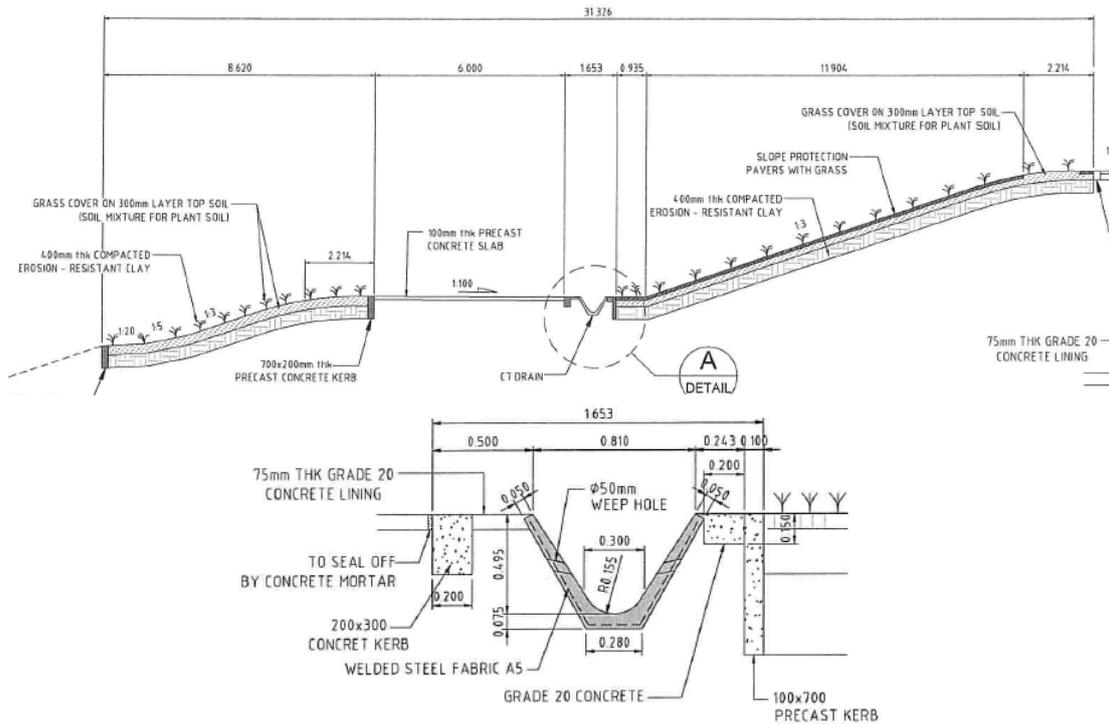


Figure 13. Cross-section of the road crossing at test plot 7.



Figure 14. Test plot 7. Collapsed channel drain and large erosion hole underneath the road section, after 31 minutes of 100 l/s per m (a condition far beyond design requirements).

As test plot 8 had the same ramp as in test plot 7, but with no drain or open pavers, it was expected that this section would be stronger. But due to unknown reasons the topsoil of the upper slope appeared to be very erodible. After 2 hours of 50 l/s per m, a condition beyond design requirements, the upper slope has eroded and the sand core has exposed. See Figure 15. Due to this early failure of the upper slope, it was not possible to test the transition from grass to ramp up to failure, and the difference in design with and without drain could not be determined.



Figure 15. Test plot 8. The final situation of upper slope seen from the road after 2 hours of 50 l/s per m (a condition beyond design requirements).

HYDRAULIC MEASUREMENTS ON THE SLOPE

In order to apply the cumulative overload method, it is necessary to measure the front velocity of overtopping wave volumes. First a dome camera on a pole was used to record the flow of overtopping wave volumes over the slope. The camera took 50 frames per second and by counting the number of frames needed for the wave front to travel 2 m, the average front velocity over these 2 m could be calculated, see the left picture of Figure 16. Secondly, paddle wheels were placed 3 cm above a plate that was mounted to the soil, see the right picture of Figure 16. The distance between the paddle wheels was 3 m along the slope. Paddle wheels measured the velocity over time at a certain location, which is different from the front velocity.



Figure 16. Left: an overtopping wave volume of 1500 l/m reaching the 12 m line 13 frames after reaching the 10 m line; front velocity 7.67 m/s. Right: Paddle wheels mounted on the grass slope, 3 cm above the slope.

Front velocities were determined for specific released overtopping wave volumes from 250 l/m to the maximum of 4300 l/m and from 2 m from the crest up to 22 m along the slope. Maximum velocities were measured at 1.5 m, 4.5 m, 7.5 m, 11.5 m and 14.5 m. Figure 17 shows all the results with the geometry of the slope in a graph.

Near the wave overtopping simulator the front velocities may differ (slightly) from maximum velocities measured with a paddle wheel. This is because when the water is first released from the simulator, the valve is not fully open and this front determines the front velocity over the first few meters. This probably explains why the graph in Figure 17 shows an increase of front velocity from 3 m to 5 m. This increase could also partly be caused by the acceleration of the water down the slope. In general, all overtopping wave volumes show an acceleration from 3 m up to about 9 m. This is expected as gravity will increase the flow over the slope. At some point the flow becomes in balance with the friction and energy dissipation of the grass and becomes more or less constant and may, due to the friction, even reduce in speed. For large velocities on the slope the front velocity and maximum velocity become similar.

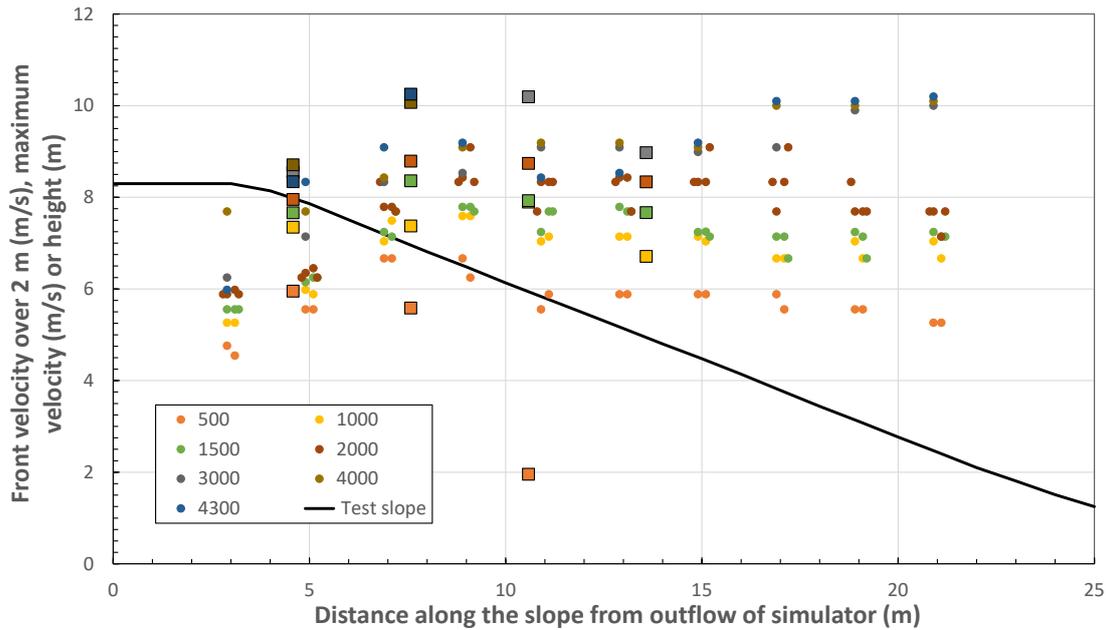


Figure 17. Averaged maximum velocities (square symbols) as a function of location on the slope, compared to front velocities (small circles). Similar colours have similar overtopping wave volumes (in l/m in the legend).

ANALYSIS OF ALL RESULTS AFTER FINAL TESTING

Analysis on critical velocity

In total 8 plots have been tested. An overview of these plots with its type of topsoil, grass type and final status after the test is given in Table 2. The first two test plots 1 and 2 were only tested up to 50 l/s per m. Test plots 3, 4, 7 and 8 failed before the 200 l/s per m test was finished. Plots 5 and 6 did not fail and succeeded the whole test up to 6 hours with 200 l/s per m.

Table 2. Overall view of tested plots with type of topsoil, grass seeded and final status after testing. In bold: the Bermuda took over the Manila Grass.

Plot	Soil type	Grass type seeded	Failure/no failure
1	CUGE	Bermuda Grass + Manila Grass	Tested till 50 l/s per m, no failure
2	CUGE	Manila Grass	Tested till 50 l/s per m, no failure
3	CUGE	Bermuda Grass	Failed at 1 h 11 min at 200 l/s per m (condition far beyond design requirements)
4	HDB	Bermuda Grass	Failed at 1 h 38 min at 200 l/s per m (condition far beyond design requirements)
5	HDB	Manila Grass	Tested till 200 l/s per m, no failure
6	HDB	Bermuda Grass + Manila Grass	Not mowed. Tested till 200 l/s per m, no failure
7	HDB	Bermuda Grass + Manila Grass	Failed at 31 min at 100 l/s per m (condition far beyond design requirements)
8	HDB	Bermuda Grass + Manila Grass	Failed at 2 h at 50 l/s per m (condition beyond design requirements)

Values of the cumulative overload damage D were calculated for each test condition, using the distribution of overtopping wave volumes in the steering files and for critical velocities of 5, 6, 7 and 8 m/s. Then the cumulative overload damage of a series of test conditions up to a certain time in the test process was calculated. The final result is given in Table 3.

Table 3 was used to find the critical velocity U_c for damage criteria that were observed during testing, like start of damage, several open spots and failure of the slope. These criteria belong to a cumulative overload of $D = 1000, 4000$ and $7000 \text{ m}^2/\text{s}^2$, respectively based on the past testing done in The Netherlands. Table 4 shows the damage criteria found and the critical velocity that was based from Table 3. The cumulative overload that corresponds with the critical velocity is also given in the last column in Table 4. For example, in test plot 3, failure of the slope was reached after 1 hour and 11

minutes testing with 200 l/s per m. The total cumulative overload after 6 hours with 1, 10, 50, 100 l/s per m and 1 hour and 11 minutes testing with 200 l/s per came to $D = 6162 \text{ m}^2/\text{s}^2$ for $U_c = 7 \text{ m/s}$ and that is close the criterion for failure of $D = 7000 \text{ m}^2/\text{s}^2$.

Table 3. Cumulative overload D (m^2/s^2) after a sequence of conditions.

Critical velocity U_c (m/s)	5	6	7	8
Overtopping discharge				
1 l/s per m, 6 hours	84	1	0	0
10/s per m, 6 hours	2273	269	6	0
50 l/s per m, 2 hours	9211	1751	141	0
50 l/s per m, 6 hours	22934	4427	351	2
100 l/s per m, 31 min	27296	6424	638	9
100 l/s per m, 6 hours	73330	27774	3632	214
200 l/s per m, 1 hour and 11 min	92388	37977	6162	420
200 l/s per m, 1 hour and 31 min	97761	40787	6865	498
200 l/s per m, 6 hours	170044	79157	16069	1418

Table 4. All test plots with established conditions for specific damage criteria and an estimation of the critical velocity U_c and its respective cumulative overload D .

Test plot	Damage criterion	Final overtopping condition	U_c (m/s)	D (m^2/s^2)
1	Several open spots at slope	50 l/s per m	6	4,427
2	Several open spots at slope	50 l/s per m	6	4,427
3	Start of damage at slope	10 l/s per m	5 - 6	269 – 2,273
	Several open spots at slope	50 l/s per m	6	4,427
	Failure, sand core reached	1 hr and 11 min. 200 l/s per m	7	6,162
4	Start of damage at slope	10 l/s per m	5 - 6	269 – 2,273
	Several open spots at slope	50 l/s per m	6	4,427
	Failure, sand core reached	1 hr and 31 min. 200 l/s per m	7	6,162
5	Start of damage at slope	50 l/s per m	6 – 7	351 – 4,427
	Several open spots at slope	100 l/s per m	7	3,632
	No failure	200 l/s per m	> 7	1,418 – 16,069
6	No start of damage at slope	200 l/s per m	> 8	1,418
	No several open spots at slope	200 l/s per m	> 8	1,418
	No failure	200 l/s per m	> 7	1,418 – 16,069
7	Start of damage to pavers	1 l/s per m	< 5	84
	Several undermining of pavers	50 l/s per m	6	4,427
	Undermining, no failure pavers	31 minutes 100 l/s per m	6	6,424
8	Start of damage at slope	1 l/s per m	< 5	84
	Several open spots at slope	10 l/s per m	< 5	2,273
	Failure of the slope	2 hours 50 l/s per m	5	9,211

If no failure was reached, then a minimum critical velocity was given. For example, test plot 6 did not fail after the full test of 200 l/s per m. A cumulative overload of $D = 16,069 \text{ m}^2/\text{s}^2$ is related a critical velocity of 7 m/s. As the slope did not fail the critical velocity is certainly larger than 7 m/s. But for a critical velocity of 8 m/s the cumulative overload is only $1418 \text{ m}^2/\text{s}^2$ and that is much smaller than the failure criterion with $D = 7000 \text{ m}^2/\text{s}^2$. One cannot say that the critical velocity should be larger than 8 m/s. Therefore, the critical velocity will be larger than 7 m/s, in between 7 m/s and 8 m/s where the cumulative overload of D is equal to $700 \text{ m}^2/\text{s}^2$.

The damage at the transition from concrete to grass slope at the crest is a specific damage. Very often start of damage occurred early and based on that the critical velocity was often estimated at $U_c < 5 \text{ m/s}$ up to 5-6 m/s or 6-7 m/s. But none of the erosion holes led to failure. The hole increased in size and depth, but the depth was never so large that it went through the subsoil. As none of these transitions failed, the critical velocity $U_c > 7 \text{ m/s}$.

Table 4 shows that the critical velocities for start of damage and for several open spots at plots 3-5 are typically in the range of 5 m/s to 6 m/s and are often 1 m/s smaller than the critical velocity for failure. Failure is classified when the topsoil and subsoil fail, i.e. the sand core is exposed. It was observed that due to flow concentration in gullies, etc. and the high flow velocities in the last test condition, lumps of subsoil were removed, leading to failure and a hole into the sand core. This could show that the topsoil, which was primarily to serve to provide a conducive environment for the grass growth, was very erodible (weak part) and the subsoil gives some residual strength.

Critical velocities from grass pull tests according to Bijlard (2016) showed values between 4.2 m/s and 6.3 m/s, which provides the strength of the grass and topsoil only and not the subsoil. This corresponds to the observations as mentioned in the above paragraph, where the critical velocities from the overtopping tests for the first two damage criteria are 5-6 m/s. If the failure criterion is taken as the removal of the topsoil onto the subsoil, then the critical velocities from the overtopping tests are 5-6 m/s.

OBSERVATIONS, CONCLUSIONS AND RECOMMENDATIONS

All objectives were met and all combinations passed the design criteria. However, the results showed that the topsoil could be improved to increase its resistance to erosion. Based on the testing, a number of observations can be made, leading to conclusions and sometimes also to recommendations.

Overtopping waves that run over the crest accelerate on the down slope due to gravity. The increase in front velocity may be 2-3 m/s and front velocities of overtopping wave volumes larger than 3000 l/m may become larger than 10 m/s. The largest velocities were found between 5-20 m from the crest and in this area most of the damage was found. It can be concluded that objectives a) and b) were fulfilled as it can be concluded that the dike is safe under design conditions and the wave overtopping tests gave a significant insight in the strength and safety of the dike.

Design conditions for the dike are around 1 l/s per m and therefore a condition of 50 l/s per m can be considered as an overload condition. All test plots passed this overload condition of 50 l/s per m. Sometimes there was damage or erosion, but failure was only found far beyond design conditions, or even no failure was observed after full testing. It can be concluded that with respect to safety of the dike, any combination of grass type and topsoil has passed the test. Even though the soil complied with the overload conditions, an improvement of this topsoil will be able to enhance the performance of the total system.

Of the 8 test plots, two plots did not fail. The topsoil of plot 5 appeared to be much stronger and showed less erosion than other plots. The reason for this is unknown. However, typically test plots 3 to 6 can withstand the wave overtopping rate up to 200 l/s per m. In test plot 6 the grass had not been mowed and the long grass acted as a kind of armour to the slope and slowed down the erosion of the topsoil. Plots 3, 4 and 8 failed due to large holes on the slope and subsequently into the sand core. Damage started with superficial overall erosion at all plots (except plot 6. This mechanism of superficial erosion had not been observed earlier by the test team in more than ten years of testing at Dutch dikes. Even not at testing pure sand dikes along a river, where the (matured) grass cover had a topsoil of sand. It must be noted, however, that this sand topsoil changed over time due to organisms in the soil and between the grass roots. The topsoil at the mock-up dike was very erodible. This could be due to the composition of the topsoil or the grass had only established for one year. Besides superficial erosion, the erosion at the weaker locations led to erosion holes and later to gully's onto the subsoil. Holes and gully's attracted water flow, finally leading to failure of the subsoil and water reaching the sand core.

The loss of grass/roots by overtopping waves was not really observed and did not initiate damage. Often large erosion holes were visible with the grass still in place. Only when the topsoil was fully eroded to the subsoil, the grass had been removed as grass roots were mainly present in the topsoil, and hardly in the subsoil. There is a distinct transition between topsoil and subsoil, and they are also completely different clays. The topsoil looks more like turf with a lot of organic material, where the subsoil is really stiff clay. The subsoil is so stiff that it cannot be considered as homogeneous. Lumps of clay were visible instead of homogeneous material and during the final phase before failure it were lumps of subsoil that were washed away.

The failure mechanism started with overall superficial erosion of the topsoil, leading to erosion holes onto the subsoil and then the subsoil acted as a residual strength and had to be removed by (large) overtopping waves. The critical velocity of the topsoil can be characterised by about $U_c = 6$ m/s, where the total system, including the subsoil, can be characterised by $U_c = 7$ m/s (failure at plots 3 and 4) or even $U_c > 7$ m/s (no failure at plots 5 and 6).

With respect to objective c) it can be concluded that there is no preference for CUGE or HDB topsoil. Both showed erosion. It is strongly recommended to improve the topsoil to a real clayey material with less or no organic material. The topsoil and subsoil differed very much. It is also recommended to find or specify a topsoil and subsoil that are more similar material.

The preferred grass is Bermuda. Although the wave overtopping tests were not decisive in a choice for Bermuda or Manila, other reasons gave a preference for Bermuda. One of the reasons is that Bermuda overtook Manila in the plots that were seeded with 50% Bermuda and 50% Manila. The seeds

of the Bermuda developed faster. It was also noted that in plot 5 some areas with Manila were taken over by other grass types and by weeds. This was not, or at least much less present for the Bermuda. The grass pull tests gave a slight preference for the Bermuda grass. It can be concluded that Bermuda grass is preferred above Manila, but this conclusion is based on the overall behaviour of the Manila grass versus the Bermuda and is not based on the wave overtopping tests.

It can be concluded that construction of concrete elements as a drain in a sand bed gives a weak spot. As soon as overtopping water can reach the sand it will be eroded with undermining as a consequence.

ACKNOWLEDGMENTS

Prof. K. d'Angremond is acknowledged for his continuous support of the testing.

REFERENCES

- Bijlard, R., G.J. Steendam, H.J. Verhagen and J.W. van der Meer. 2016. Determining the critical velocity of grass sods for wave overtopping by a grass pulling device. *ASCE, Proc. ICCE 2016*, Antalya, Turkey.
- EurOtop. 2018. Manual on wave overtopping of sea defences and related structures. An overtopping manual largely based on European research, but for worldwide application. Van der Meer, J.W., Allsop, N.W.H., Bruce, T., De Rouck, J., Kortenhaus, A., Pullen, T., Schüttrumpf, H., Troch, P. and Zanuttigh, B., www.overtopping-manual.com.
- Hoffmans, G., A. van Hoven, G.J. Steendam and J.W. van der Meer. 2018. Summary of research work about erodibility of grass revetments on dikes. *Proc. 3rd Int. Conf. on Protection against Overtopping*, June 2018, UK.
- Steendam, G.J., A. van Hoven, J.W. van der Meer and G. Hoffmans. 2014. Wave Overtopping Simulator tests on transitions and obstacles at grass covered slopes of dikes. *ASCE, proc. ICCE 2014*, Seoul, South Korea.
- Steendam, G.J., J.W. van der Meer, P. van Steeg and G. van der Meer. 2013. Hydraulic test facilities at dikes in situ. *Proc. ICE, Coasts, Marine Structures and Breakwaters 2013*, Edinburgh, UK.
- Steendam, G.J., J.W. van der Meer, B. Hardeman and A. van Hoven. 2010. Destructive wave overtopping tests on grass covered landward slopes of dikes and transitions to berms. *ASCE, Proc. ICCE 2010*, Shanghai.
- Van der Meer, J.W. 2017. Simulators as Hydraulic Test facilities at dikes and other coastal structures. Chapter 1 in *Series of Coastal and Ocean Engineering Practice, Vol.2. Design of Coastal Structures and Sea Defences*. Ed. Y.C. Kim.
- Van der Meer, J.W., A. van Hoven, G.J. Steendam and G. Hoffmans. 2018. Hydraulic simulators on real dikes and levees. *Proc. 3rd Int. Conf. on Protection against Overtopping*, June 2018, UK.
- Van der Meer, J.W., B. Hardeman, G.J. Steendam, H. Schüttrumpf and H. Verheij. 2010. Flow depths and velocities at crest and inner slope of a dike, in theory and with the Wave Overtopping Simulator. *ASCE, Proc. ICCE 2010*, Shanghai.