USE OF WAVE IMPACT GENERATOR AND WAVE FLUME TO DETERMINE STRENGTH OF OUTER SLOPES OF GRASS DIKES UNDER WAVE LOADS

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Outer slopes of grass dikes under wave attack are likely to have residual strength, which is the strength after initial damage has occurred. This strength is not included in current design and assessment tools. To quantify the residual strength of grass under wave attack and implement this in design and assessment tools, a large research program is initiated within the Dutch WTI 2017 project. This project is financed by Rijkswaterstaat. In this research program an integrated approach, a combined use of a so-called wave impact generator and large-scale wave flume tests in the Delta Flume is applied. This approach contributes to a future strength model which includes residual strength of the outer slope of grass dikes under wave loads, primarily along large rivers.

Grass cannot be scaled properly and many variations exist in grass covers (clay quality, grass quality, transitional structures, objects in or on the dike, et cetera). For this reason, testing with traditional physical wave flume models would lead to unacceptable high costs since many tests are required. Therefore, a wave impact generator is developed (Van Steeg et al, 2014). This machine can be placed easily on a prototype dike in the field and can generate wave impacts on a slope. During testing, the machine is continuously filled by a pump. By opening a pre-programmed valve irregularly, a mass of water is relieved leading to an impact that resembles impacts caused by natural waves.

The developed wave impact generator is applied in an extensive measurement campaign on several grass dikes in the Netherlands. Variations of the thirteen different test sections were on grass and clay quality but also transition structures and objects (pole, open concrete blocks allowing grass growth, stairs). This leads to valuable erosion patterns as function of geometric properties of the outer slope of the dike. The hydraulic load during all tests was the same.

Although wave run-up levels and wave impact pressures due to the wave impact generator are close to natural waves, there is a need to calibrate the results obtained with the wave impact generator. Therefore, large scale physical model tests in the Delta Flume, with a selection of the dikes tested with the wave impact generator, are performed. Blocks of 2 m x 2 m x 0.8 m were taken from dikes and were transported to the Delta Flume. In this flume (L x B x D = 235 m x 5 m x 7 m), waves can be generated up to a significant wave height of $H_s = 1.6$ m.

Erosion patterns obtained with the wave impact generator and erosion patterns obtained in the large scale flume were compared. Based on this comparison and based on impact pressure analysis it is concluded that the wave impact generator represents a load which is equivalent to a significant wave height of $H_s = 0.6 – 0.7$ m, a wave steepness of $s_{op} \approx$ 4-5%.

The integrated use of the wave impact generator and a large-scale wave flume led to valuable data. This data will be used to improve the strength model for outer slopes of grass dikes under wave attack.

Keywords: wave impact generator, grass slope, wave attack, wave flume

INTRODUCTION

Within the Dutch research project WTI 2017 (“Research and development of safety assessment tools of Dutch flood defences”), one of the projects is about the residual strength of grass on river dikes under wave attack. Residual strength is the remaining strength of a dike after initial damage occurred. The focus of the research was on the wave impacting zone of the outer slope of a dike. The relevant range of significant wave heights was estimated at $H_s \approx 0.5$ to 0.8 m and a wave steepness of $s_{op} \approx 4\%$ - 5%, which is based on the Dutch riverine conditions.

To investigate the residual strength of grass on river dikes under wave attack, it was chosen to combine research with a full-scale wave flume (Deltares Delta Flume) and a so-called wave impact generator. With this wave impact generator a schematised load, which resembles wave impacts as a result of wave breaking on a slope, is generated. A wave impact generator is a tank filled with water that can be quickly opened with a special valve on a predetermined way. This results in water falling on the dike causing a hydraulic load (‘impact’) on the dike followed by a run-up and a run-down of the water mass. An impression of the Delta Flume and of the wave impact generator is given in Figure 1.

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Figure 1. Impression of testing grass dikes in the Deltares Delta Flume (left and middle) and with use of the wave impact generator (right).

The objective of the use of the wave impact generator was to compare the following influences on the strength of river dikes: (1) the grass quality, (2) the clay quality, and (3) the influence of transition structures or objects.

The objective of this paper is to (1) give an overview of the tests with different grass and clay qualities which were performed with the wave impact generator, (2) to give an overview of the tests performed in the Delta Flume and (3) to obtain a first estimate of the erosion rate of a grass slope under wave attack with initial damage.

DEVELOPMENT OF WAVE IMPACT GENERATOR

The wave impact generator was developed for the aim of this project and is described in Van Steeg (2012a, 2012b, 2013a) and summarised in Van Steeg et al (2014). A brief summary is given in this section. The wave impact generator can be placed on a real existing dike and is able to generate a sequence of impacts on a slope. This sequence is close to impacts caused by natural waves. The wave impact generator is developed in four steps:

1) Study and parameterization of wave impacts based on full-scale wave flume (Delta Flume) pressure measurements on a block revetment (Van Steeg, 2012a)
2) Design, testing, and analysis of prototype wave impact generator with use of several pressure meters (Van Steeg, 2012a), see also Figure 2.
3) Adaptation of wave impact generator and testing with several pressure meters (Van Steeg, 2012b).
4) First testing in the field and improvements to optimize testing procedure (Van Steeg, 2012c).

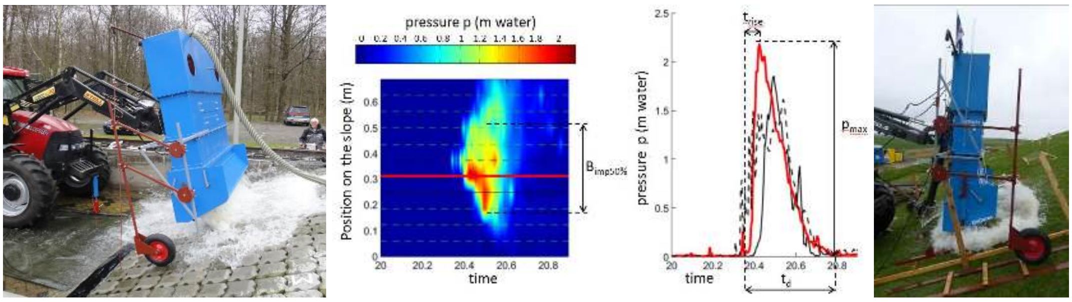

Figure 2. Left: testing of wave impact generator on a concrete slope equipped with pressure meters. Middle-left: impression of pressure as function of time and positions on the slope, Middle-right: impression of pressure on a specific location as function of time. $B_{imp50\%}$, t_{rise}, t_d, and p_{max} are parameters which describe the parameterized impact and are explained in Van Steeg (2014). Right: prototype testing in the field.

The wave impact generator works as follows: During operation the wave impact generator is continuously being filled by pumping water in the water tank. With closed valves the water level in the water tank will increase. By opening the valves, the water in the tank is suddenly released through a special designed outflow compartment and will lead to an impact on the slope. The valves open and close automatically after a predetermined irregular period. The different opening time intervals lead to different water levels and thus to different peak pressure which gives the pressure distribution as given in Figure 3. During operation the wave impact generator is attached to a tractor and stabilized by supporting legs. Every twenty impacts (a so-called sub-cycle) the wave impact generator is moved by the tractor to a different location on the slope to simulate the distribution of impact location. Three sub-cycles form a complete cycle. Depending on the response of the structure (damage of grass and clay) some tests require up to hundreds of cycles. The number of impacts can be translated to storm duration by applying the following formula:

$$t_{storm} = \frac{1}{3600} \cdot \frac{N}{\chi} \cdot T_m \cdot f \qquad (1)$$

where t_{storm} is the storm duration (hours), N is the number of impacts by the wave impact generator, χ is the fraction of waves simulated (e.g. the highest 33% waves except for the highest 2% waves are simulated with the wave impact generator. The value of χ is therefore equal to 33% - 2% = 31% = 0.31), T_m is the mean wave period of the prototype wave field and f is a correction factor which should be applied to correct for model effects of the wave impact generator.

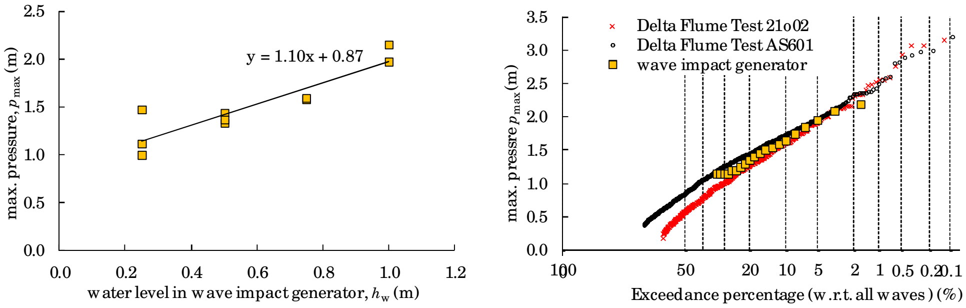

Figure 3. Left: peak pressure (p_{max}) as function of water level (h_w), right: Exceedance curve of peak pressure p_{max} for wave impact generator and for full-scale measurements performed in the Delta Flume. By varying the water level h_w, the maximum pressure p_{max} can be varied and the exceedance curve of the reference tests can be reproduced.

As can be seen in the right graph in Figure 3, wave impacts with an exceedance of approximately 33% - 2% can be simulated. The wave impact generator is intended to give a hydraulic load which results in an erosion rate of the same order of magnitude as real waves on Dutch river dikes. The present design of the wave impact generator allows the creation of a range of impacts, corresponding with a range of wave heights as encountered in a random wave field at these dikes. For the present research it was chosen to produce only a specific range of wave impacts corresponding to an estimated significant wave height of $H_s \approx 0.7$ m and a wave steepness of $s_{op} \approx 4\% - 5\ \%$. Since only the large impacts give a significant contribution to erosion, only the (approximately) largest one-third of the impacts, with exception of the highest 2% of waves, were generated. Unfortunately it was not possible to generate the highest 2% of the wave impacts due to practical reasons.

TESTS IN THE FIELD WITH THE WAVE IMPACT GENERATOR

Introduction and overview of tests

To identify the influence of the grass quality, the clay quality and the presence of objects and transitions, several tests at real existing dikes were performed with the wave impact generator. This paper describes the five tests with various grass and clay qualities. An overview of these tests is given in Table 1. The tests on transitions and objects are subject of a future publication.

Table 1. Overview of tests performed with wave impact generator on real existing dikes

Test	Type	Slope	Grass quality		Soil quality			
			sod cover	root density	type of soil	< 2 μm (clay)	2 μm < < 64 μm (silt)	> 64 μm (sand incl. gravel)
Oo.1	Grass	1:3	99%	high	low res. clay	18%	32%	50%
Ha.1	Grass	1:3	86%	poor	low res. clay	14%	17%	69%
Be.1	Grass	1:3	98%	moderate	sand	0%	4%	96%
Ol.1	Grass	1:2.5	78%	poor	sand	2%	10%	88%
Ol.3	Grass	1:2.5	64%	poor	sand	2%	8%	90%

The tests are categorized based on the grass quality (sod cover and root density) and the soil quality (type of soil and composition of soil) which is explained in the two following sections.

Grass quality

The sod cover is determined by using a grid in a 50 x 50 cm frame with 81 measuring points. Where necessary for easier measurement, the vegetation is cut back to a height of about 2 cm. For every grid intersection (measuring point) a long needle is pressed perpendicularly into the sod, and it is determined whether there is 'plant contact' or 'ground contact'. The number of measuring points with 'plant contact', relative to the total number of measurement points, is a measure of the percentage sod cover.

The root density is estimated by the so-called ‘hand method’ as described in Sprangers and Arp (1999). A gouge auger with a diameter of three centimetres is used to sample the top 50 cm of the grass sod, which is divided into layers of 2.5 cm thickness. In each layer, the number of root fragments of > 1 cm length is estimated as a measure of root density. In each sample plot, three root density measurements were carried out. Afterwards, the root densities for the three separate measurements were averaged for the sample plot. Based on this count, the quality of the sod root density is expressed in four categories: ‘very poor’, ‘poor’, ‘moderate’ and ‘good’. Illustrations of the determination of the sod cover and the determination of the root density are given in Figure 4.

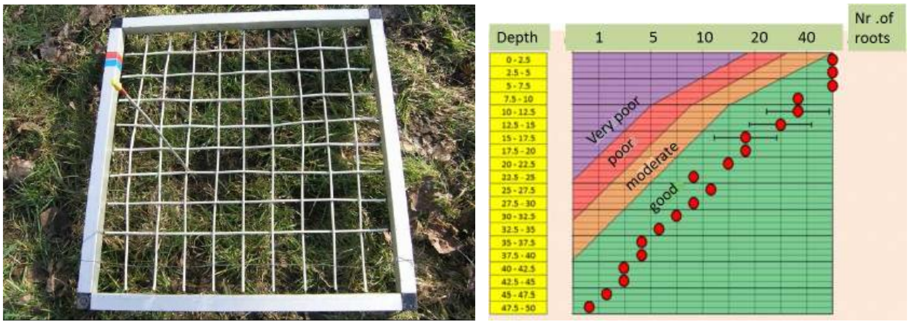

Figure 4. Left: grid to determine sod cover. Right: Example of determination of root density.

Soil quality

The soil quality is expressed in the type of soil (sand, low resistance clay and high resistance clay) and the composition of the soil. The type of soil is determined based on the Attenberger diagram as given in Figure 5. The Attenberger limits are given by determining the liquid limit LL (water content at transition from plastic to liquid) and the plastic limit PL (water content at transition from solid to liquid). The plasticity index PI can be determined by subtracting the liquid limit and the plastic limit or:

$$PI = PL - PP \qquad (2)$$

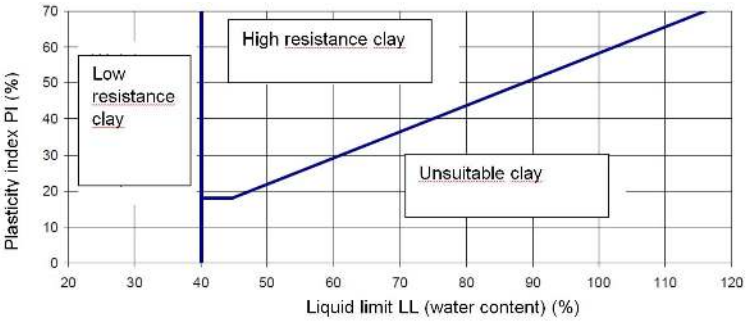

Figure 5. Attenberger limits.

The composition of the soil is based on the fraction of clay (< 2 µm), silt (2 µm < < 63 µm) and sand (> 63 µm) which is based on the classification as given in ENW (2012).

An impression of the four dikes on which tests were performed is given in Figure 6.

Figure 6. From left to right: impression of location Oosterbierum (Oo.1), Berkum (Be.1), Harculo (Ha.1), and Olst (Ol.1).

Description of test procedure with wave impact generator

The test procedure is reported in Steendam (2012) and Galema and Mom (2013). This section gives a brief overview. The experimental set-up consisted of the wave impact generator, a hydraulic crane to position the wave impact generator, a pump for water supply (approximately 200 m^3/hour), facilities to house operating staff, and measurement equipment. The measurement equipment consisted of a 3D laser scanner to measure the erosion pit, cameras to record the test and tools for hand measurements.

Prior to testing the soil was watered for at least 72 hours before a test was carried out. Prior to testing artificial initial damage was made to the grass slope. This damage was a cylindrical shaped erosion pit with a depth of 20 cm and a diameter of 30 cm.

After a sequence of wave impacts with the wave impact generator the test was interrupted to measure the erosion pit. An impression of the development of the erosion is given in Figure 7 (Oo.1), Figure 8 (Ha.1), Figure 9 (Be.1) and Figure 10 (Ol.1).

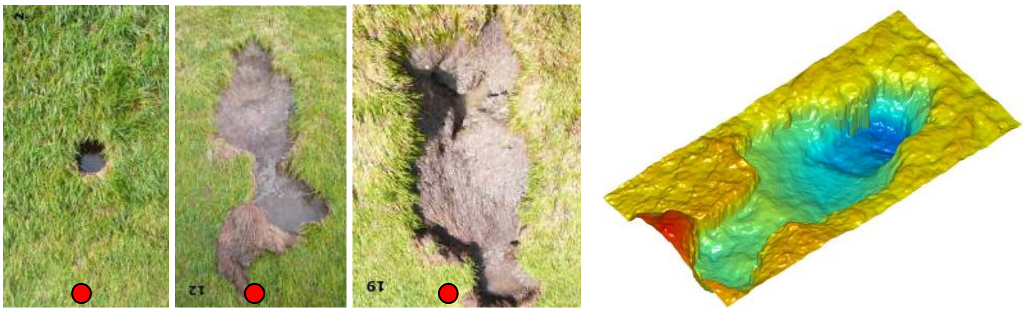

Figure 7. Erosion development of Test Section Oo.1 (artificial damage, after 1086 impacts, after 4001 impacts) and 3D difference plot based on laser measurement. (Red dot indicates the ‘toe side’ of the test section)

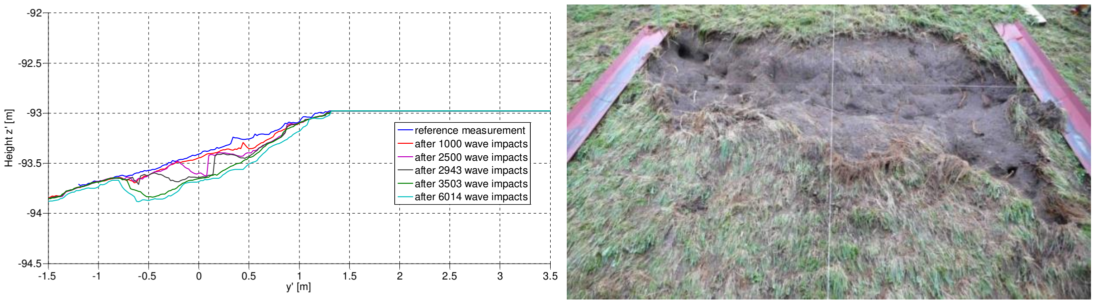

Figure 8. Test Section Ha.1. Left: erosion development, right: test section after 6014 impacts.

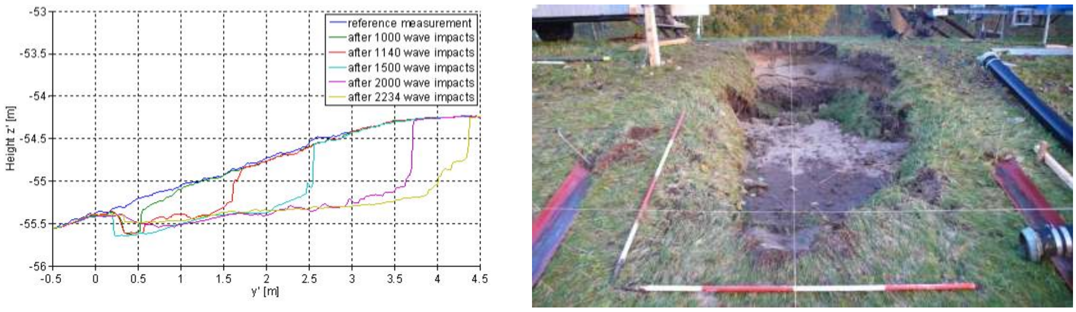

Figure 9. Test Section Be.1. Left: erosion development, right: test section after 2234 impacts.

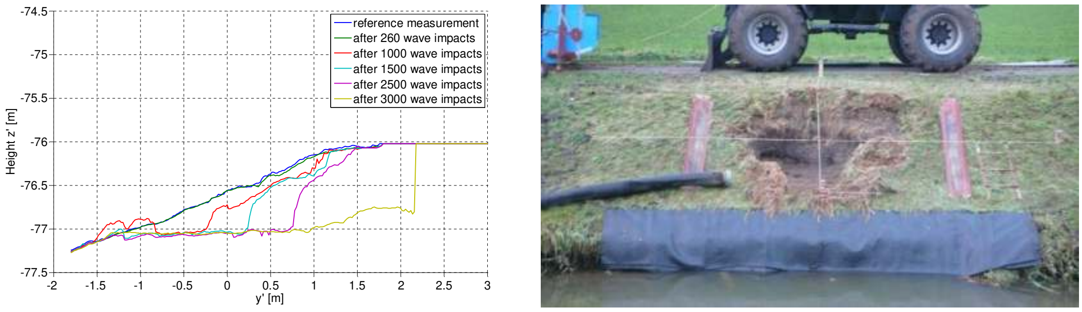

Figure 10. Test Section Ol.1. Left: erosion development, right: test section after 3000 impacts.

Based on the measurements the maximum erosion depth (d_{max}) and the surface of the eroded plane (perpendicular to the crest of the dike) were determined for each measurement. This is shown as function of the duration (t) in Figure 11. Duration t is determined with use of Eq. (1).

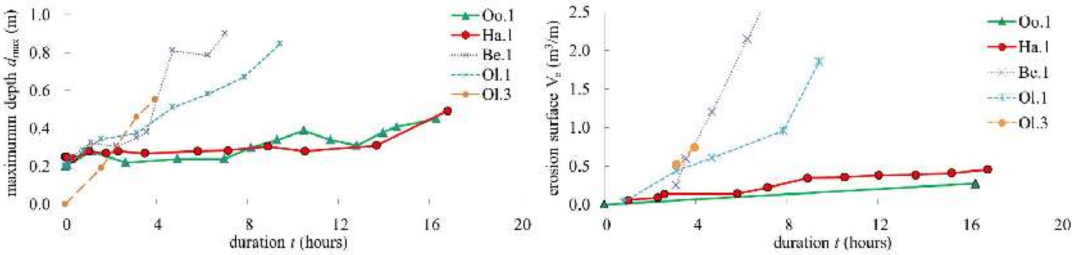

Figure 11. Maximum depth d_{max} (left) and erosion surface V_e (right) as function of duration t

FULL SCALE TESTS WITH DELTA FLUME

Introduction

Full scale tests were carried out in the Delta Flume of Deltares. This flume has a length of 235 m, a width of 5 m, and a depth of 7 m. Wave fields with a significant wave height up to H_s = 1.6 m can be generated in this flume. An impression of this flume during testing is given in Figure 1.

The tests are described in detail in Van Steeg (2014) and are summarized in this section. The test set-up was constructed in such a way that two test sections could be tested simultaneously. It was chosen to test location Harculo (Ha.1) and location Oosterbierum (Oo.1) since these dikes represent a significant part of the riverine dikes in the Netherlands and these dikes were tested with the wave impact generator (see previous chapter).

Construction of test set-up

The construction of the test set up consisted of two phases: 1) collection of the grass-clay blocks from the real existing dike and 2) placing the blocks in the Delta Flume. The collection of the blocks was performed by using steel frameworks of 2 m x 2m x 1 m which were pressed into the dike (see Figure 12). Then a steel plate was pressed under the steel framework and the grass-clay block was removed from the dike (see Figure 13).

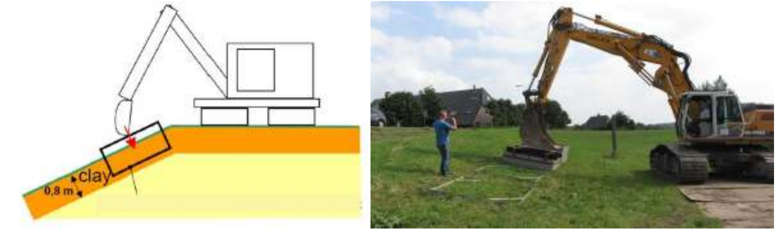

Figure 12. Pressing of steel framework into the dike.

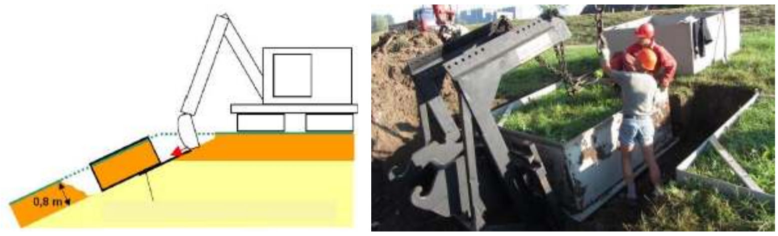

Figure 13. Shifting of steel plate under grass block and removing the grass block from the dike.

The blocks, including the steel frames, were transported to the Delta Flume and were placed in the flume. After placement, the steel frames were removed (see Figure 14). At both sides eight blocks were placed in the flume leading to a test surface of 2 m x 16 m for each test section. The thickness of the test section was approximately 0.75 m. In between the two test sections a 1 m wide concrete smooth dummy section was constructed. Between the dummy section and the two test sections steel plates were placed to avoid lateral water movement between the sections.

Figure 14. Placement of the grass-clay blocks in the Delta Flume.

Test programme and measurements

Four test series with different significant wave height (H_s = {0.5 m; 0.7 m; 0.9 m; 1.1 m}) were performed. The wave steepness s_{op} was approximately 4.5 %. An overview of the tests is given in Table 2. The tests were performed on three different locations of the dike (by changing the water level between the different test series). Since no damage occurred at Test Section 2 (H_s = 0.5 m) this section was used again for Test Section 4. A test was carried out until the erosion was significant or until a large test duration (20 hours of testing) was obtained.

The measurements that were obtained were wave height measurements and erosion measurements. During testing the test were stopped several times to measure the erosion. This was done with a 3D laser scanner and by hand.

Table 2. Overview tests performed in the Delta Flume

Test Section	H_{m0} (m)	s_{op} (-)	t (hours)
1	0.7	0.047	19
2	0.5	0.049	20
3	0.9	0.050	15
4*	1.1	0.044	10

*at location of Test Section 2

Condition of grass and clay

The grass-clay blocks were collected at the same dikes as where tests with the wave impact generator were carried out (Oo.1 and Ha.1, see previous chapter). Likewise, the same grass and clay conditions were expected which was generally also the case. At the Harculo side of Test Section 1 a clear hole due to mice / mole activities was observed. At the Oosterbierum side of Test Section 1 some sand inclusions in the clay were observed. The clay appeared to be relatively heterogenic.

The artificial initial damage had a cylindrical shape with a depth of 20 cm and a diameter of 30 cm. The location of this shape was made at the position where the maximum impact pressure was expected.

Description of tests and test results

An impression of testing is given in Figure 1. During all tests except for Test Section 2 (H_s = 0.5 m) the erosion pit deepened and widened during testing. In this paragraph the damage development of Harculo Test Section 1 is given as an example. The other tests sections are described in Van Steeg (2014).

A photograph of the damage after one hour is given in Figure 15. Further damage progression is given in Figure 16, which is based on laser scan measurements. Based on the laser scans, cross surface plots were made. The cross surface was made perpendicular to the slope and parallel with the flume axis. An example of the development of the cross surface plane is shown in Figure 17. The cross surface shown is the maximum measured cross-surface in the considered area.

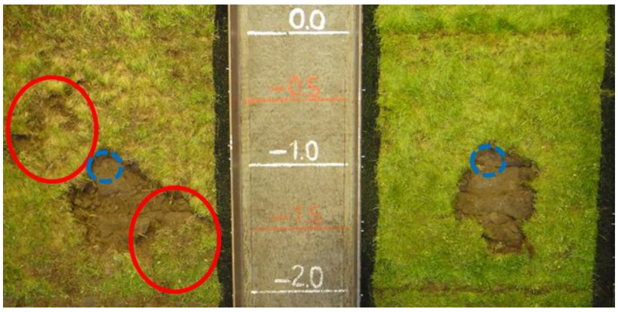

Figure 15. Damage after 1 hour at Test Section 1 (left: Harculo, right: Oosterbierum). Blue circles indicate artificial initial damage, red circle.

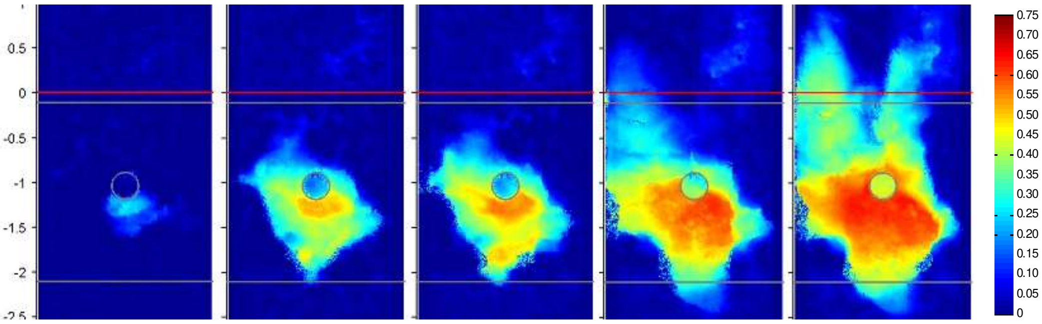

Figure 16. Impression of damage development (difference plot) of Test Section 1 (H_s = 0.7 m), Harculo (t = {1h, 5h, 7h, 13.5h, and 19h}).

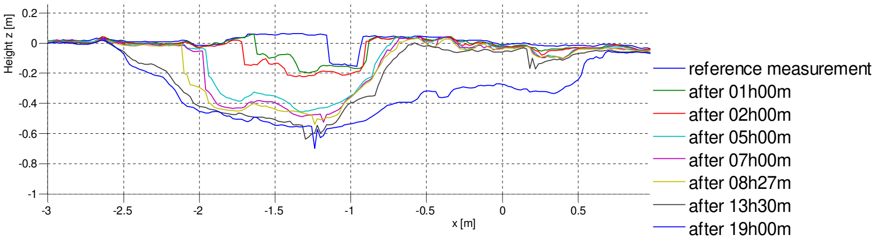

Figure 17. Profile at position with maximum erosion of surface of cross section (Harculo, Test Section 1).

Based on the measurements a maximum depth (d_{max}) and a maximum eroded surface (V_e) of a cross section could be determined for each measurement. This resulted in the graphs given in Figure 18 and Figure 19 where these parameters are plotted as function of test duration *t*. In these graphs also the test results obtained with the wave impact generator are plotted. For these tests, the duration (*t*) is determined with use of Eq. (1).

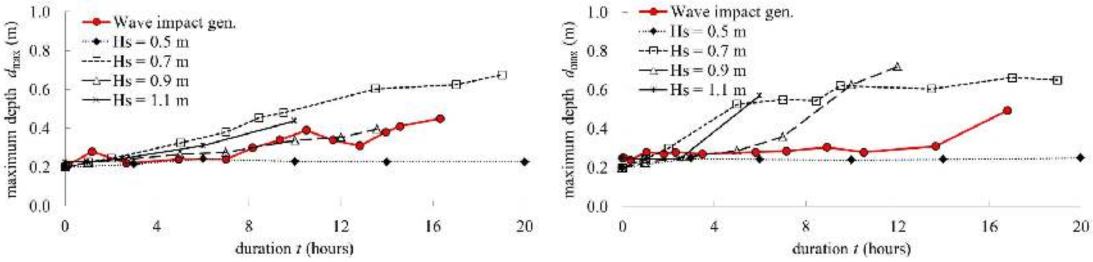

Figure 18. Maximum depth d_{max} as function of test duration *t* (left: Oosterbierum, right: Harculo).

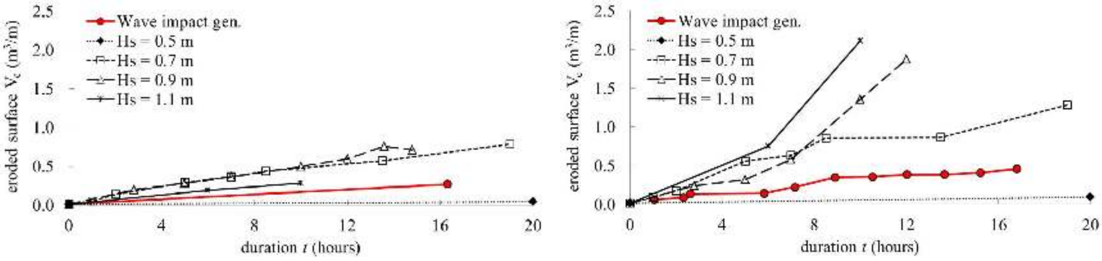

Figure 19. Maximum eroded surface V_e as function of test duration *t* (left: Oosterbierum, right: Harculo).

ANALYSIS

Quantification of erosion rate of tests in the Delta Flume

The erosion rate of the tests in the Delta Flume is determined in two ways:

- Based on maximum depth d_{max} of erosion pit (mm/hour)
- Based on maximum eroded surface of the cross section V_e of the erosion pit (m^3/hour per meter dike).

A third possible parameter could be the eroded volume (m^3). It was chosen not to analyse this since this specific parameter was often influenced by side effects (presence of flume walls).

To determine a representative erosion rate R_e, a linear relation of erosion as function of duration t was assumed. This was done in two ways: Method 1 (average measured erosion rate) and Method 2 (maximum measured erosion rate) which are both based on the measured data as given in Figure 18 and Figure 19. In Method 1, the representative erosion rate is based on initial damage ($t = 0$ hours, $d_{max} = 0.2$ m) and the average of the last two measurements. In Method 2, the maximum measured erosion rate between two measurements during a test is considered as the representative erosion rate. The erosion rate based on Method 1 and Method 2, with d_{max} chosen as erosion parameter, is given as function of the significant wave height in Figure 20. The erosion rate obtained with the wave impact generator, as obtained at these test sections in the field, is given as a horizontal dotted line.

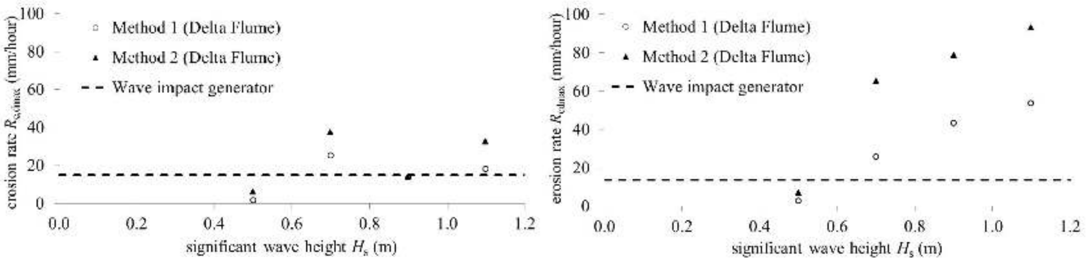

Figure 20 Erosion rate (depth d_{max}) as function of significant wave height H_s (left: Oosterbierum, right: Harculo). The erosion rate due to the wave impact generator is given as a horizontal dotted line.

The test programme was designed in such a way that it would be possible to derive the influence of the significant wave height H_s on the erosion rate R_e. However, because each test series with a certain wave height had to be carried out on a different part of the slope, differences in grass and clay quality influenced the results. (An example is Oosterbierum Test Section 1, $H_s = 0.7$ m, which contained a lot of sand, leading to relatively fast erosion). Based on Figure 20 it is concluded that these differences dominate the test results for the Oosterbierum test sections. To cope with this problem, a certain relation between the significant wave height H_s and the erosion rate R_e is assumed. The scatter of the measurements around this relation is due to the differences in grass and clay quality. From previous research and from the test results of the Harculo test section (especially according to Method 1), it is assumed that there is a linear relation between the significant wave height H_s and the erosion rate R_e, with a certain threshold wave height. Under the threshold wave height there is hardly any erosion, and above it there is a linear increase with increasing H_s.

This way of analysing the results is the best possible, given that in each test series not only the wave height but also the grass and clay quality were different due to the strong heterogenic character of grass and clay. A simple linear relation between H_s and the erosion rate is chosen, because the number of measurements is only small and the present measurements indicate such relation. A linear relation between the significant wave height H_s and the erosion rate R_e can also be noticed in the measured average erosion (Method 1) for Oosterbierum. If we regard the measurement at $H_s = 0.7$ m as an outlier, a clear linear relation can be seen, which is quantified as follows:

$$R_{e,\mathrm{x}} = a_x \cdot H_s + b \tag{3}$$

With $R_{e,x}$ is the erosion rate. With $x = d_{max}$, the erosion rate is based on the maximum erosion depth d_{max}; $R_{e,dmax}$ (mm/hour). H_s is the significant wave height (m), a_x is a coefficient for the erosion rate. With $x = d_{max}$, the coefficient is based on d_{max} ; $a_{d,max}$ (mm/(h m). b is a coefficient (mm/hour). It is likely that there is a threshold value for H_s (below this value no erosion occurs). Based on the graphs it is assumed that no erosion occurs ($R_{e,x} = 0$) for $H_s < 0.5$ m or:

$$R_{e,\mathrm{x}} = 0 \qquad \text{for } H_s < 0.5 \text{ m} \tag{4}$$

$$R_{e,\mathrm{x}} = a_x \cdot (H_s - 0.5) \qquad \text{for } H_s \geq 0.5 \text{ m} \tag{5}$$

Now the parameter a_x can be chosen in several ways. In this analysis this is done based on Method 1, Method 2 and a combination (envelop) of Method 1 and Method 2. An example of the combined method is given in Figure 21.

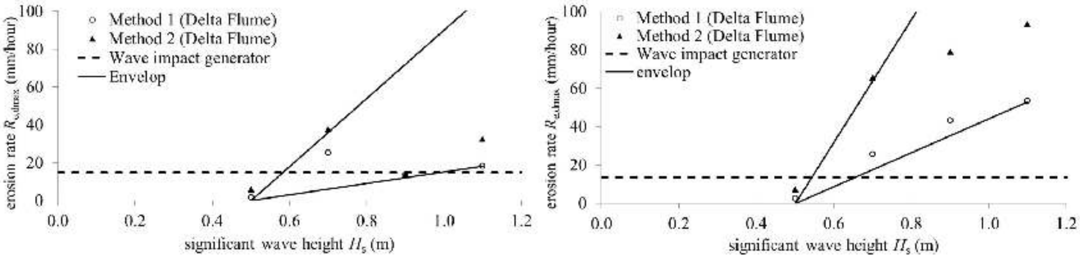

Figure 21 (linear) Envelop around measured data based on maximum erosion depth d_{max} (left: Oosterbierum, right: Harculo)

The above given analysis is performed while taking the maximum erosion depth d_{max} as damage parameter. The same analysis was performed while taking the maximum erosion surface of a cross section V_e ($a_x = a_{Ve}$ and $R_{e,x} = R_{e,Ve}$) as damage parameter. That analysis is given in Van Steeg (2014). The results are given in Figure 22.

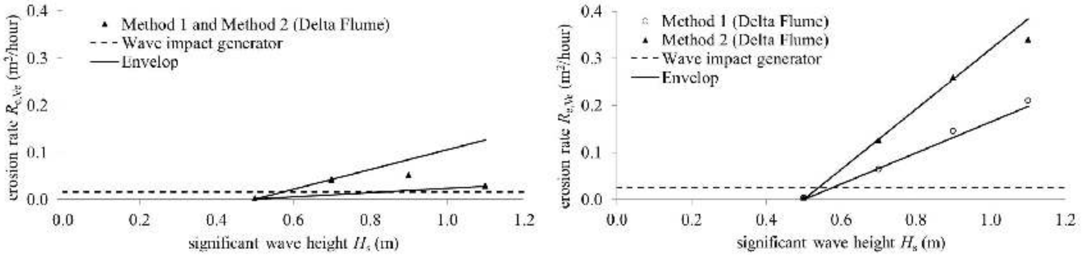

Figure 22 (linear) Envelop around measured data based on surface of cross section V_e (left: Oosterbierum, right: Harculo)

As can be seen in the analysis given above, the erosion can be expressed in several ways. Two principle choices are:

- Erosion based on the maximum erosion depth d_{max} or the maximum eroded surface of a cross section V_e.
- Erosion based on Method 1 (average erosion rate during testing) or Method 2 (maximum erosion rate in between two measurements during testing) or a combination of Method 1 and Method 2.

Overviews of the determined coefficients that can be applied in Eq. (5) are given in Table 3 and Table 4.

Table 3. Determined coefficient $a_x = a_d$ (based on maximum depth d_{max}, see Eq. (5))

Coefficient a_d	Oosterbierum all data	Oosterbierum selected data*	Harculo all data
Method 1	30 - 125	30 - 35	88 - 130
Method 2	30 - 180	32 - 53	153 - 320
Combination Method 1 and Method 2		30 - 53	88 - 320

Table 4. Determined coefficient $a_x = a_{Ve}$ (based on erosion of cross surface, V_e see Eq. (5))

Coefficient a_{Ve}	Oosterbierum all data	Oosterbierum selected data*	Harculo All data
Method 1	0.047 - 0.21	0.047 – 0.13	0.33 – 0.37
Method 2			0.56 – 0.64
Combination Method 1 and Method 2			0.33 – 0.64

* Oosterbierum Test Section 1 (H_s = 0.7 m) is excluded due to strong influence of sand in this part of the test section

Eq. (4), Eq. (5), and the values given in Table 3 and Table 4 can only be used for conditions which are comparable with the tested section (same grass and clay quality) and for the same hydraulic conditions (0.5 m < H_s < 1.1 m, $s_{op} \approx 0.04 - 0.05$). In a later stage of this project an extension of this strength model will be determined in which the results obtained with the wave impact generator (lower grass and clay quality, transitions et cetera) will be included. This strength model can be implemented in future design and assessments tools.

Comparison Delta Flume and wave impact generator

In Van Steeg et al (2014) it was concluded that the hydraulic load of the wave impact generator is comparable with the hydraulic load of an irregular wave field with a significant wave height of $H_s \approx$ 0.6 m - 0.7 m and a wave steepness of $s_{op} \approx$ 0.04 - 0.05. This conclusion was solely based on an analysis of the hydraulic pressures. It is now also possible to compare the erosion due to the wave impact generator and the erosion due to the Delta Flume which is described below.

The main goal is to find an equivalent significant wave height ($H_{s,equi}$) for which the results with the wave impact generator are as identical as possible with the results obtained in the Delta Flume. This can be done since tests with four different significant wave heights were performed in the Delta Flume leading to erosion rates as function of the wave height as given in Figure 21 and Figure 22. Based on the damage progression of tests with the wave impact generator and the Delta Flume an equivalent wave height ($H_{s,equi}$) can now be determined. Assuming identical physical processes in the Delta Flume and the wave impact generator, the erosion rate of the wave impact generator ($R_{e,wig}$) is in theory the same as the erosion rate in the Delta Flume ($R_{e,flume}$) for a certain significant wave height ($H_{s,equi}$) or:

$$R_{e,\mathrm{flume}} = R_{e,wig} \tag{6}$$

Eq. (6) can be rewritten, based on Eq. (5) as follows:

$$a_x (H_{s,equi} - 0.5) = R_{e,wig} \tag{7}$$

Rewriting Eq. (7) gives:

$$H_{s,equi} = \frac{R_{e,wig}}{a_x} + 0.5 \tag{8}$$

This value of $H_{s,equi}$ can also be read from the intersections of the lines given in Figure 21 and Figure 22. Results from this analysis are given in Table 5. These are given as maximum and minimum of the range based on the combined method (Method 1 and Method 2) and all data included.

Table 5. Determined equivalent significant wave height H_s for wave impact generator based on erosion rate

	Harculo	Oosterbierum
	Based on d_{max}	Based on d_{max}
$H_{s,equi}$ (m) based on d_{max}	0.54 – 0.65	0.57 – 1.00
$H_{s,equi}$ (m) Based on V_e	0.54 – 0.59	0.57 – 0.83

Although the ranges given in Table 5 are, due to the heterogenic character of clay and grass, relatively large it can be concluded that, based on the damage progression, an equivalent significant wave height of H_s = 0.6 m – 0.7 m seems plausible.

DISCUSSION

Discussion on heterogeneity

A relatively large variation of the erosion rate was measured. This is likely due to the heterogeneity of the clay and grass. Based on the experience gained in this research it is concluded that it is likely that erosion is strongly influenced by:

- Local differences in grass and clay quality
- Sand inclusions such as sand lenses
- Mice and mole holes

Local differences were, for example, found at Harculo Test Section 3 (Delta Flume). During this test, two erosion pits were formed and a section in between these pits did hardly erode at all (see left picture in Figure 23) indicating differences in the strength of the slope. Sand lenses were detected during the collection of blocks at the Oosterbierum dike, see middle photo in Figure 23. At several places mice or mole holes were observed, see right photo in Figure 23.

Figure 23. Left: erosion pattern at Harculo Test Section 3 in Delta Flume. Middle: sand lenses observed during collection of blocks of Oosterbierum. Right: Mouse hole

Heterogenic characteristics of the grass and the soil will logically lead to heterogenic erosive behaviour which was also measured during the tests. There is a challenge how the heterogenic characteristics of grass dikes have to be parameterised for model development.
It is believed that these will partly level out since we are interested in the time until the clay and grass is completely eroded away. This implies that we look at erosion of large volumes, usually containing lumps of good and lumps of poor quality clay.

Discussion on the applicability of the wave impact generator

The wave impact generator can be used to compare several situations with each other. The hydraulic load and the erosion rate is in the same order of magnitude as wave impacts due to a wave sequence with a significant wave height of H_s = 0.6 m – 0.7 m. It is expected that grass dikes with a better clay quality than the clay in Oosterbierum or Harculo does not lead to erosion when testing with the wave impact generator. If required, the wave impact generator can be adapted to create larger impacts (e.g. by lifting the wave impact generator to a larger height which lead to higher loads, see Figure 24). For grass dikes with a comparable or lower strength the present wave impact generator can be used to obtain benchmark data to compare several situations (difference in grass and clay quality, influence of transitions and object) with each other.

Figure 24. Impression of alternative wave impact generator that can generate impacts with a larger load.

CONCLUSIONS AND FUTURE WORK

Several tests with the wave impact generator were carried out in the field on real existing dikes. Five tests had different clay and grass qualities which are described in this paper. Other tests with transition structures and objects will be described in a future publication. Two tests which were performed with the wave impact generator were also tested in a full scale wave flume. The erosive behaviour of these two grass-clay combinations were measured and analysed, which led to a preliminary erosion model which can be implemented in a future strength model.

The erosion due to loads induced by the wave impact generator is in the same order of magnitude as ‘natural’ waves in the wave flume with a significant wave height of $H_s \approx 0.6$ m – 0.7 m and a wave steepness of $s_{op} \approx 0.04 - 0.05$. Although the loads of the wave impact generator are in the same order of magnitude as real waves, results of tests obtained with the wave impact generator should not be considered as an absolute value; the results are however very suitable to compare different situations, such as clay and grass quality, presence of transitions and object et cetera, with each other.

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