Strength of the grass sod on dikes during wave overtopping

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STRENGTH OF THE GRASS SOD ON DIKES DURING WAVE OVERTOPPING

MASTER THESIS

As partial fulfilment of the requirements for the degree of Master of Science in Hydraulic Engineering at Delft University of Technology

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Abstract

There is a shift in the approach for designing coastal structures. In the past, dikes were designed on the probability of exceedance of an incoming wave during storm conditions. In the near future, the design criteria will be the probability of flooding of the hinterland. In order to determine this flooding probability, the strength of the dike has to be known. This thesis focuses on the erosion of the grass sod during overtopping wave volumes. Several tests have been performed in the last few years with the wave overtopping simulator. During this thesis, some of these locations have been tested for the strength of the grass sod with a newly developed method. This new method, called the sod pulling method, tests the actual strength of the grass by lifting the grass sod out of the top layer. However, this method makes at least two cuts in the sod in order to attach the pull frame. So a methodology has to be developed to calculate the strength of an intact grass sod from the measured data.

The measured forces needed to lift the grass sod can be rewritten into critical grass normal stresses for an intact sod, which can be done with a practical method developed in this thesis. In this method a shape factor is introduced to compensate for the influence of the cuts made in the sod before testing. Because of the heterogeneity of the grass sod, the individual test results are not the most important parameters. In order to determine the representative strength of the grassed slope during wave overtopping conditions, the strength of the weakest sections in the grass sod have to be determined. This can be done by assuming a normal distribution for the strength of the grass, where the 2.5% tail value will be used as the governing strength of the sod. In order to determine the parameters of the normal distribution, at least 30 tests are needed to be done as condition 2 test with the 20 by 20 centimetres frame size under saturated conditions, at random locations on the bottom half of the slope.

The square root of the calculated critical grass normal stress is one of the input parameters in the critical velocity formula, which also uses the pore water pressure, the relative turbulence intensity and the density of the water. When the critical velocity resulting from this formula is compared with the determined critical velocity during the wave overtopping simulations, there is good correspondence between the values for the tested locations in this thesis. So the sod pulling test can provide results that are reliable enough to determine the critical velocity of a dike section.

Executive Summary

Introduction

There is a shift in the approach for designing coastal structures. In the past, dikes were designed on the probability of exceedance of an incoming wave during storm conditions. In the near future, the design criteria will be the probability of flooding of the hinterland. In order to determine this flooding probability, the strength of the dike has to be known. Due to the current state of the dikes in the Netherlands, there are plans to raise the crest of the dike in order to ensure the safety of the hinterland. During extreme storm conditions waves will overtop the crest which can lead to erosion of the grass sod on the landward slope. This in turn can result in instability of the dike and flooding of the hinterland.

In order to determine the erosion of the grass sod during wave overtopping, several tests have been performed in the last few years with the wave overtopping simulator. When there is a good description of the failure mechanisms of a dike during wave overtopping conditions, it can show the real strength of the dike. This will avoid unnecessary rejections of dikes for lack of knowledge, which leads to excess safety of the dike. A critical velocity has been determined with the wave overtopping simulator per location as a parameter for the strength of that dike section. The critical velocity is one of the input parameters in the Cumulative Overload Method, which is used to determine the strength of a dike under overtopping wave volumes.

At some of these tested locations, the strength of the grass sod has been determined with a newly developed testing method. This new method, called the sod pulling method, tests the actual strength of the grass by lifting the grass sod out of the top layer. This is done by inserting pins into the sod. These pins are attached to a pull frame which is lifted out of the grass sod by a hydraulic cylinder. In order to insert the pins into the sod, the soil has to be excavated on two sides (condition 2 test) or on all 4 sides (condition 4 test). This has the disadvantage that the strength of an intact sod cannot be measured directly. So a method has to be determined to calculate the strength of an intact grass sod.

The report can be divided into three main sections. The first part gives theoretical background information over the strength of grass sod. The second part consists of the data analyses from the sod pulling tests done during this thesis. The third part determines the critical velocity of a grassed slope on a dike. The next paragraph will give elaborate conclusions based on these three sections. This will be followed by an answer on the main research question, which is formulated as:

"Can the results from the sod pulling test be used to determine the critical velocity of grassed slopes on dikes in the Netherlands during wave overtopping conditions?"

Conclusions

In order to answer the research question, several topics are defined. These topics have been divided into two subjects: the strength of the grass sod and the critical velocity of the grass sod. Per topic a number of conclusions will be given. The conclusions will be clear and concise. After each conclusion a short explanation is given.

Strength of the grass sod

a. _The structure of a grass sod on dikes in the Netherlands_

A literature study on the structure of a grass sod resulted in more insight into the behaviour and the strength of the grass. The most important conclusions have been summarized here.

1. _A grass sod has a structured but heterogeneous build-up, where the roots provide most of the resistance against the erosion during wave overtopping._

   A grass sod consists of multiple layers in vertical direction, which all have their own structure. They all have their contribution to the resistance against the erosion of the sod during wave overtopping. Multiple parameters influence the strength of the sod. They can be divided into three categories: natural (small animals), man-made (tracks, fences) and weather (seasonal, temperature, rainfall) influences. A grassed slope can be very heterogeneous in structure and strength, where the weakest part is most susceptible to erosion.

2. _Saturation of the grass sod has a large influence on erodibility of the cover layer during wave overtopping conditions._

   The saturation of the cover layer determines the size of the suction pressures acting on the sod. These pressures have to be overcome first in order to lift the grass sod out of the ground. They vary greatly under different conditions, but when the ground is fully saturated (which is the case during most wave overtopping conditions), the suction pressures reduce to zero.

b. _Available methods of determining the grass strength on dikes_

Different methods for determining the strength of the grass sod on dikes have been developed in the Netherlands. Several conclusions can be drawn from them.

3. _Different locations use different maintenance types for the grass sod. This results in a different strength of the sod._

   In this research the old method of determining the grass strength based on the maintenance type is checked for accuracy with the sod pulling device. The different tested locations in this thesis are Millingen aan de Rijn and four sections at the Boonweg near Sint Jacobiparochie, which all use different types of maintenance. This difference is an important research item in this thesis, since it is useful to know which type of maintenance results in the strongest grass sod. The expected quality of the grass sod based on the type of maintenance is:
   - Boonweg 3 and Millingen: Good quality grass
   - Boonweg 1, 2 and 4: Moderate quality grass.

   This distinction in strength is also expected to return in the results of the sod pulling tests at these locations.

4. _The available methods of determining the grass sod quality have limitations when looking for the strength of grass during wave overtopping._

   There are in total (including newly developed methods) 7 methods available for determining the strength of the grass sod. However, none of these methods determine the exact strength of the grass. They use certain characteristics which can be related to the strength, but there is no quantitative link with the actual strength of a sod. Furthermore, these methods neglect most local weak spots. Erosion during overtopping waves is most likely to start at these spots, which may expand to large erosion holes. A method is required to determine weakest spots in the sod, since it will be decisive for the strength of the entire dike section.

c. *The sod pulling test and a comparison it with the current methods available*

The sod pulling test is the main component in this thesis. Since it is developed two years ago a short introduction is necessary in order to gain awareness of the operations of the device.

5. *The sod pulling method is a practical way of determining the strength of the grass sod.*

For the testing of the strength of the grass a simple testing method is preferred, since dike managers may use it in the future to test their dike sections. During the sod pulling test the vertical force required to lift a grass sod out of the top layer is measured. Four pins are anchored into the sod at 4 centimetres below the surface, to prevent the pins from tearing through the sod. In order to insert the pins into the sod, the soil has to be removed from at least two sides of the frame (see Figure 1a). Because of this, it is not possible to test the strength of an intact grass sod. The sod is lifted by a hydraulic cylinder which is manually operated with a steering wheel (see Figure 1b). This cylinder induces an increasing displacement on the grass sod, until the sod fails and is pulled out of the sod (Figure 1c). During the tests the force and displacement have been measured (and stored) four times a second. This data can be used for the analyses of the strength of the sod.

There are many variations possible with this test set-up, like saturation of the sod, different frame sizes and so on. There are also two testing conditions of the grass sod:
- Condition 2 test: The frame will be placed on top of a sod, where 2 sides were cut before testing. The other 2 sides and the bottom of the sod will provide resistance against the uplifting force.
- Condition 4 test: The frame will be placed on top of a sod where all the sides were cut. This way, only the bottom of the sod will resist against the imposed displacement of the hydraulic cylinder.

These tests conditions can be used to calculate the strength of an intact sod (see Conclusion 9), which in turn will be used for the analyses of erosion during wave overtopping.

Figure 1a,b,c - Different stages during the sod pulling tests: Top view condition 4 test (a); Test set-up (b); Pulled out sod (c)

*d. **Different influences on the measured strength of the grass sod following from the results of the sod pulling test***
In this thesis approximately 160 tests have been performed with the sod pulling device, which enables to investigate different sod properties. These tests lead to the following conclusions.

6. *Data from all the individual sod pulling tests per location are to be combined to find an average and standard deviation for the strength of the tested section.*

   As a grass cover is very heterogeneous, the results from the similar type of sod pulling test differ quite a lot from one another, even for tests close to each other. This can also be for areas that visually look the same. Because of this, the individual tests are not the most important data. All the data collected with the sod pulling test will be combined into an average value, with a standard deviation and a corresponding coefficient of variation. These data are assumed to be more reliable compared to each individual test.

7. *Unsaturated soil experiences suction pressures in the sod, which can increase the resistance of the grass sod against the uplifting forces by a factor of 1 to 1.4 depending on the degree of saturation.*

   During storm conditions the cover layer of the sea dike will be completely saturated. There are no suction pressures left in saturated soil, leading to less resistance against uplifting of the sod. In order to simulate these conditions during the sod pulling tests the soil has to be watered artificially before testing. However, the governing wave overtopping conditions at river dikes can occur with unsaturated soil conditions, due to high river discharges in summer time. So it is important to see how much these suction pressures exactly contribute to the strength.

   The influence of the saturation of the top layer is tested by doing some tests under unsaturated conditions. These tests resulted in higher values for the measured forces compared to the tests under fully saturated conditions. Depending on the degree of saturation the suction pressures result in a measured force with a factor up to 1.4 higher for unsaturated soil. However, there is not yet enough data for determining this factor exactly, so the sod pulling tests should be performed under saturated sod conditions at sea dikes.

8. *A frame size of 20 by 20 centimetres should be used for testing to give the most reliable results*

   Different frame sizes have been used during the tests. The 10 by 10 centimetre frame size leads to inaccurate results, since the local deviations (due to the heterogeneity of the sod) have too much influence on the outcome. Therefore, the results from this frame size are not used in the analyses for the strength of the grass sod. The 15x15 centimetre and 20x20 centimetre frame sizes have a larger area of testing, which reduces the influence of local deviations. The coefficient of variation of these two frame sizes is in order of 15%, which leads to more reliable results. However, during the cutting of the sides, the sod is disturbed on local scale. For larger frame sizes these disturbances have less influence on the end result because of the larger area of the sod. Frame sizes larger than 20 by 20 centimetres cannot be lifted with the current sod pulling device, therefore testing with the 20 by 20 centimetres frame size is preferred in further research.

e. ***A methodology for calculating the strength of an intact grass sod from the results of the sod pulling test***

The sod pulling tests have been performed as condition 2 or 4 tests (number of sides cut), because it is not possible to test the strength of an intact grass sod. However, during wave overtopping the grass sod is still intact before erosion starts, so it is important to determine a method for estimating the strength of an intact grass sod from the results of the condition 2 and condition 4 tests.

9. *The practical approach for determining the critical grass mean normal stress (indicator for the strength) of an intact grass sod provides better results compared to the theoretical approach developed by Hoffmans. In the practical approach a small shape factor (1.10 to 1.20 depending on the frame size) is introduced to compensate for the cutting of the sides and corners before testing. The practical approach uses two equations.*

$$\sigma_{grass,c} = \frac{F_i}{A_b + 4 * A_s} \qquad with \qquad F_i = \alpha * [F_2 + (F_2 - F_4)]$$

There are two methods available for determining the strength of an intact grass sod.

1. The theoretical approach by Hoffmans (2012), based on the exponential decrease of the root density over the depth. However, this method leads to inconclusive results, because the values for the critical grass mean normal stress are not in the same order for the condition 2 and 4 tests. The condition 4 tests give significantly higher stresses compared to the condition 2 tests. Both test methods should give approximately the same results, since the tests are all performed on the same cover layer.

2. A practical approach is developed in this thesis and is based on the relation between the condition 2 and 4 test. A problem with this method is that the sides are cut before testing, which influences the strength and the shape of the sod. Especially the corners of the sod are influenced by this cutting. Therefore a shape factor α is introduced. The shape factor has a value between 1.10 and 1.20 depending on the frame size used. For the practical method a relation between the condition 2 and 4 test has to be assumed. It is possible to match the measured force from condition 2 test with a measured force from a condition 4 testing method. This matching can be done by arranging them on measured strength, where the largest condition 2 force (F_2) is matched with the largest condition 4 force (F_4). This is possible because a large F_2 means that it was a locally stronger part of the grass layer. The same holds true for a large F_4. Therefore it is possible to compare both tests with each other. The strength of an intact sod is divided by the total area of the sod (bottom area A_b and the area of the 4 sides A_s), in order to find the critical grass mean normal stress.

When the two approaches are compared, the practical approach gives more constant, but significant lower values for the critical grass mean normal stress, than the theoretical approach. This can be explained by the fact that the theoretical approach is based on an ideal situation, where coverage and amount of herbs do not influence the root density. Furthermore, saturation and maintenance have no effect on the outcome in the theoretical approach. It is assumed that the practical approach gives more accurate results. So this method is used for further analyses in this thesis.

10. *It is possible to calculate the strength of an intact sod directly from the measured value of the condition 2 test, by multiplying the measured force with an amplification factor of 1.56.*

A disadvantage of the sod pulling method is that two testing methods have to be combined in order to find the strength of an intact sod. Therefore twice the number of tests has to be performed in order to determine the strength of the grass sod. However, it is possible to

calculate the strength of the intact grass sod directly from the condition 2 test with an empirical factor. This factor is (almost) constant, independent of the location and frame size used (excluding the 10x10 frame). So it is possible to perform only condition 2 tests, after which the measured force is multiplied by an amplification factor of 1.56 to determine the force needed to extract an intact sod. This way, the total number of tests needed, can be halved by excluding the condition 4 tests from the test set-up.

f. ***Different grass sod properties related to the strength of the sod***
The sod pulling tests have resulted in better understanding of the behaviour of grass under a vertical displacement. The most important conclusions are stated below.

11. *The previous assumed strength of the grass based on the maintenance type is not in accordance with the measured strength during the wave overtopping simulations and the sod pulling tests. Grazing by sheep seems to be beneficial for the strength of the grass sod on dikes.*

During this research four different maintenance types were tested in order to compare the results with the old method of determining the strength based on different maintenance types. The expected strength on the basis of the theoretical approach is different from the strength determined with the sod pulling tests and with the wave overtopping simulations. Boonweg 1, 2 and 4 are expected to have a moderate grass strength and Boonweg 3 and Millingen a higher strength, see Conclusion 3. However, this is not the case, as can be seen in Figure 2.
The most important difference between the tests and the theoretical method is the influence of grazing on the strength of the grass sod. Boonweg 3 and Millingen do not allow grazing on the dike which results in a lower average strength found during wave overtopping and the sod pulling tests. Boonweg 1,2 and 4 do allow grazing on the slopes, but only Boonweg 4 results in a lower strength. This section does twice a year hay-making, which can possibly have negative influence on the strength. The difference between Boonweg 1 and 2 is the use of fertilization. This difference would suggest that the usage of fertilizers has negative influence on the strength of the sod. This is in accordance with the accepted theory.
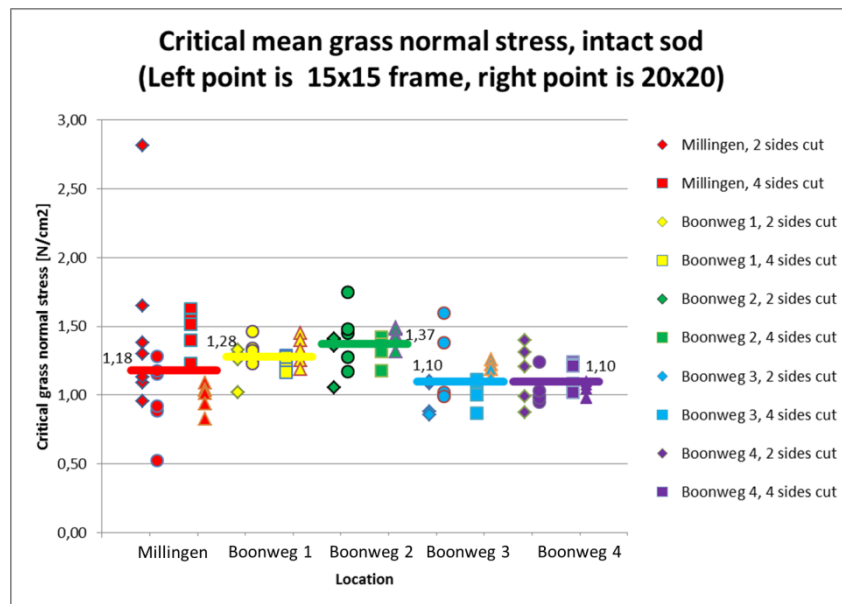

Figure 2 - Critical mean grass normal stress per location

12. *A grass sod is influenced by fatigue. After the sod has reached a certain vertical displacement, some roots break leading to a weaker sod, even after the external force is removed. It requires a smaller force to reach the same elevation.*

The fatigue tests are performed as condition 2 or 4 tests for all three frame sizes. During these tests the sod is pulled up for a certain displacement and then released back to its original position. This imposed displacement is repeated 10 times, after which the displacement is increased by 5 millimetres. The first pull per imposed displacement requires the highest force to reach this elevation. The force needed, decreases per pull until the 4th repetition. From there on, the force levels out to a constant level. This process is observed every time after increasing the displacement.

During the condition 2 fatigue tests it was possible to look underneath the grass sod at higher elevations. This means that the bottom roots had failed, but the sides still provided some resistance against the displacement. The roots inside the side walls require larger displacements before failure occurs. This can also explain the bulging mechanism encountered during some of the wave overtopping simulator tests at the Boonweg.

13. *Contradictory to the findings of Hoffmans, pinewood is not comparable in behaviour with a grass sod, since it has a Modulus of Elasticity of a factor 100 larger than a grass sod.*

The modulus of elasticity provides insight into the strength of a grass sod under multiple repeating loads. It is therefore a factor which determines the fatigue of a sod. If a grass sod can be compared to another (better known) wood like product, the fatigue behaviour of that material could be used as estimation for the fatigue of a grass sod. In order to compare different materials, the modulus of elasticity (or Young's Modulus) should be the same. This modulus is a measure for the stiffness of an elastic material and is defined as the ratio between the stress and the deformation. In previous research a link is made with the modulus of elasticity of pinewood, which has an E-modulus around 9 GPa. However, the E-modulus of the grass sod is around 0.1 GPa, so the materials are not comparable in behaviour.

14. *When the grass sod is eroded from the top layer, the underlying clay still provides resistance against the uplifting force. At 6 cm depth about 70% of the original value is required to lift the sod. At 10 cm depth this is about 45%.*

The structure of the landward slope of a dike is generally the same. The top layer consists of a grass sod built on a clay layer of minimal 70 centimetres thick. During wave overtopping small areas of grass can erode away, but the underlying clay layer still provides some resistance against the overtopping waves. This clay layer protects the core of the dike. When the clay is eroded, the dike core will be exposed leading to failure of the dike section. Therefore it has been tested in this thesis how strong the remaining clay layer is. The clay is tested at 6 cm depth and at 10 cm depth. At 6 cm depth there are more roots present compared to the test at 10 cm depth. These roots provide extra resistance against the erosion.

The force needed to extract a clay sod at 6 cm depth is about 70% of the maximum strength needed for a normal grass sod. The strength of the clay sod at 10 cm depth is about 45% of the original strength. It was established in previous research that the strength of pure clay of decent quality was only 0.075 N/cm^2 (Hoffmans, 2012). The values found with the sod pulling test are significantly higher, since they are in the order of 0.5-0.9 N/cm^2. Therefore the few roots and the resulting structured clay have an enormous impact on the strength of the clay layer.

Critical velocity of the grass sod

g. *The Cumulative Overload Method*

The average wave overtopping discharge (q) is not the best parameter for determining the strength of the grass sod on dikes during wave overtopping. This is because the larger overtopping waves generate higher loads on a slope, which is not accounted for in the average wave overtopping discharge. Therefore the Cumulative Overload Method is developed by Van der Meer in 2010, to provide a better relation between the amount and velocity of the overtopping waves and the strength of grass.

15. *The Cumulative Overload Method is given by*

$$D = \sum_{i=1}^{N} (\alpha_M U^2 - \alpha_s U_c^2) \qquad for\ \alpha_M U^2 > \alpha_s U_c^2$$

Where the following damage factors can be applied for the grass sod on the slope
- *No sign of damage* $\sum(U^2 - U_c^2) = 1000 \leq D \leq 7000\ m^2/s^2$
- *Start of damage* $\sum(U^2 - U_c^2) = 1000\ m^2/s^2$
- *Various open spots* $\sum(U^2 - U_c^2) = 4000\ m^2/s^2$
- *Failure* $\sum(U^2 - U_c^2) = 7000\ m^2/s^2$

In the equation above the damage factor is given as *D*, the velocity of the overtopping wave as *U* and the critical velocity as U_c. *N* is the number of overtopping waves with a higher velocity than the given critical velocity. The critical velocity is a threshold parameter that represents the strength of the grass sod during wave overtopping. When the velocity of the overtopping wave exceeds the critical velocity, damage can start to occur. Numerous waves overtop the dike during storms, each with a different volume and velocity. The more large waves overtop the crest, the more likely that damage will occur on the slope at the landward side. The Cumulative Overload Method is a decent method for describing the strength of the grass sod during overtopping waves.

The α_M is an amplification factor (≥ 1) for the increase of the velocity of the overtopping waves around obstacles or transitions. The α_s is a reduction factor (≤ 1) for the decrease in strength of the grass sod around obstacles and transitions.

The damage factor for "No sign of damage = $1000 \leq D \leq 7000\ m^2/s^2$ is established in this thesis in order to find a critical velocity for two Boonweg sections that showed no sign of damage during the wave overtopping simulations. This damage factor should at least be lower than the failure criteria, but an estimation of <1000 m²/s² could also be valid because there is no start of damage. This leads to two values between which the critical velocity should be. It is not yet possible to give a more accurate estimation for this criterion, because the first two damage criteria (start of damage and various open spots) are not always visible during wave overtopping simulator tests.

h. The critical velocity formula and its relation with the sod pulling test

The goal of this thesis is to find the relation between the critical velocity in the Cumulative Overload Method and the results from the sod pulling tests. In order to find this relation, more insight is needed into the critical velocity. Hoffmans developed a formula for the critical velocity, which will be used as the basis for this relation.

16. *The equation for the critical velocity (U_c) derived by Hoffmans et al. in 2008 can be used to link the critical velocity towards the sod pulling tests, by means of the critical grass mean normal stress ($\sigma_{grass,c}$). The equation is given below.*

$$U_c = \alpha_{grass,U} \; r_0^{-1} \sqrt{\frac{\Psi_c \; (\sigma_{grass,c}(0) - p_w)}{\rho}}$$

In the above equation r_0 is the relative turbulence of the overtopping wave over the slope. This is an important and relatively unknown parameter, since turbulence is difficult to measure. First estimations for the relative turbulence are between 0.1 and 0.3. Ψ_c is the Shields parameter for transport of soil under flow velocities, which is used as a constant of 0.03. $\sigma_{grass,c}$ is the critical mean normal stress which has to be determined for the grass sod. The pore water pressure (or suction pressure) is given as p_w, which increases the strength of the unsaturated soil, since the suction pressures should be overcome before the grass sod can be lifted up. The density of the water is given by ρ and $\alpha_{grass,U}$ is a constant with the value of 2.

The equation gives decent results for the critical velocity when comparing them with the results from the wave overtopping simulations. However, some parameters have a rather large uncertainty and are therefore further investigated in this thesis.

17. *A normal distribution can be assumed for the strength of the grass sod per dike section. The 2.5% tail on the weaker side of this distribution is assumed representative for the strength of grass sod during wave overtopping.*

During the sod pulling tests the measured forces are rewritten into critical grass mean normal stresses with the practical method. These stresses are assumed to be normally distributed with an average value and a corresponding standard deviation. There is quite some deviation in the results of the normal stress needed to lift a certain grass sod. When waves overtop the crest of the dike, damage can start to occur at the weakest sections of the dike. The damage started at some of these points, may slowly expand until it creates an erosion hole. This hole will increase in size and will eventually lead to the failure of the dike. So the representative strength of the dike is not the average, but the weakest section(s).

There are two limits generally used for the tail of a normal distribution, the 90% and the 95% limit. These limits imply that 90% (or 95%) of the results from the sod pulling tests will be between certain values at either side of the average. These values however are for both Gaussian tails, thus leading to a 5% or 2.5% limit for the weakest part. The 2.5% limit is can be used as an estimation of the area of multiple open spots susceptible for erosion, compared to the total area of the slope. The 2.5% tail can be calculated by the average value subtracted with the standard deviation times factor 1.96. The resulting value can be used as the governing critical grass mean normal stress for the dike section.

18. *To determine the parameters of the normal distribution for the strength of a dike section, at least 30 sod pulling tests need to be performed. These need to be performed as rapid condition 2 test with the 20 by 20 centimetres frame size under fully saturated conditions. The location of each test needs to be selected at random at the bottom half of the slope.*

In this thesis five locations are tested with the sod pulling test for their strength. At each location a minimum of 20 tests were performed. With these 20 tests results an acceptable indication for a normal distribution was found. The more tests performed the better the parameters of this distribution resemble the real distribution of the strength of the grass sod. Therefore it is recommended to do at least 30 sod pulling tests per dike section for new tests. In order to find the parameters of the normal distribution, all tests need to be performed at random spots since it is not possible to visually find the weakest spots. During wave overtopping simulations most of the damage occurred at the bottom half of the slope, so it is recommended to test this section of the slope. The other testing conditions follow from Conclusion 7, 8 and 10.

19. *The equation from Conclusion 16 is rewritten into a more practical equation for the relation between the sod pulling tests and the critical velocity. In this formula has the square root of the critical grass mean normal stress a linear relation with the critical velocity of the slope.*

$$U_c = \alpha_{grass,c} \; r_0^{-1} \sqrt{\frac{(\sigma_{grass,c}(0) - p_w)}{\rho}}$$

Note that in this new equation $\alpha_{grass,U}$ is replaced by $\alpha_{grass,c}$ to include the Shields parameter in the factor. The Shields parameter is based on the transport of loosely packed sand on a river bed. This is not exactly comparable with the erosion (or movement) of the grass sod during wave overtopping conditions. However, the Shields parameter does give an indication of this movement. Emmerling came to approximately the same conclusion for fluctuating pressure forces acting on particles. Both methods came to a value of 0.03, which is assumed to be also applicable for grass erosion. This value is used as a constant for every location and can be removed as an input parameter from the equation and added to the $\alpha_{grass,U}$ factor in order to get a more practical equation, so $\alpha_{grass,c} = \alpha_{grass,U} * \sqrt{\Psi_c} = 0.34$.

The pore water pressure is still in the equation, since suction pressures can result in much higher critical velocities. However, during the wave overtopping tests the ground becomes saturated over time. At the beginning of the tests, only small (low velocity) waves run over the slope, resulting in (almost) no damage, but decreasing the suction pressures. At the moment that the governing wave conditions overtop the crest during the simulation, the ground is fully saturated and the pore water pressure is zero. However, in real storm conditions the ground might not be completely saturated when the governing wave conditions overtop the crest. So the pore water pressure cannot be removed from the equation.

The relative turbulence intensity has an important role in the formula for the critical velocity. This factor is normally between 0.10 and 0.20 for overtopping waves on a slope. The further down the slope the higher the velocity on that section and therefore the lower the relative turbulence intensity. During the wave overtopping simulations at the tested locations most of the damage occurred at the bottom half of the slope, so a value close to 0.10 should be used. The relative turbulence intensity factor is fitted on a value of 0.12, given the 2.5% value of the weakest spots. When damage is found higher up the slope, the relative turbulence intensity can be increased up to a maximum of 0.20 for damage at the crest of the dike.

Answer research question

The main research question in this thesis is:

"Can the results from the sod pulling test be used to determine the critical velocity of grassed slopes on dikes in the Netherlands during wave overtopping conditions?"

The answer to this question can be summarized into:

The sod pulling test can be used as a predictor for the strength of the grass sod. It provides results that are reliable enough to determine the critical velocity of a dike section. The forces measured during the tests need to be rewritten into critical grass normal stress ($\sigma_{grass,c}$), which is one of the input parameters in the equation below for determining the critical velocity of the grass sod. The other parameters included in the formula are the relative turbulence intensity (r_0), pore water pressure (p_w) and the density of the water (ρ).

$$U_c = \alpha_{grass,c} \; r_0^{-1} \sqrt{\frac{(\sigma_{grass,c}(0) - p_w)}{\rho}}$$

Table 1 gives the critical grass mean normal stresses determined with the sod pulling tests and the critical velocities of the tested dike sections. The "calculated" values are the outcomes from the sod pulling tests in combination with the critical velocity formula. The "determined" values have been defined during the wave overtopping simulations. There is a strong correlation between both values for the critical velocity at the tested locations, especially when the "no sign of damage" criterion of 1000 m^2/s^2 is used. This leads to the assumption that Boonweg 1 and 2 are stronger than expected based on the wave overtopping simulations, where they were thought to have approximately the same strength as Boonweg 3 and 4. On the other hand, if the critical velocity of the Boonweg 1 and 2 is indeed only a bit higher than 8 m/s (if D = 7000 m^2/s^2), the sod pulling tests still give a decent approximation of the strength for these locations.

Table 1 - Critical velocity per location estimated from the sod pulling tests (calculated values) and wave overtopping simulator tests (determined values)

Location	Critical grass tensile stress [N/cm2]			Critical Velocity [m/s]		
	μ	σ	2.5 % limit	Calculated	Determined	Difference
Millingen	1,18	0,27	0,65	7,23	7	3%
Boonweg 1	1,28	0,10	1,08	9,33	8 - 9.5	2 - 16%
Boonweg 2	1,37	0,14	1,10	9,38	8 - 9.5	1 - 17%
Boonweg 3	1,10	0,17	0,77	7,85	8	-2%
Boonweg 4	1,10	0,14	0,83	8,14	8	2%

Recommendations

It needs to be noted that some aspects need further investigation, before the sod pulling device can be used to determine the strength of the grass sod during wave overtopping. The most important aspects are the influence of the relative turbulence (r_0) and the pore water pressure (p_w). In addition, the fatigue of a grass sod and its influence on the critical velocity should be further examined.

The most important recommendation is to validate the established relation between the critical velocity calculated with the sod pulling tests and determined with the wave overtopping simulator tests. This should preferably be done with new wave overtopping simulations. When there are no simulations planned in the near future, it is possible to test the sod pulling method at locations where wave overtopping simulations have been performed in the past. It would also be interesting to check the critical velocity of the Boonweg 1 and 2 again with the simulator in order to determine the size of the damage factor for the "no sign of damage".

Preface

After an intensive period of approximately eleven months working on this thesis, I am glad to present this report to finalize my master study Hydraulic Engineering at the University of Technology in Delft. During this period I experienced more and more that Hydraulic Engineering and especially Coastal Engineering is a very interesting branch.

I am grateful for the opportunity presented by INFRAM to work on the topic of the strength of the grass sod during wave overtopping conditions. This topic was interesting, diverse and challenging at times. The wave overtopping simulator tests triggered my interest in the subject of wave loads on sea- and river dikes. The wave overtopping loads are very important nowadays with current state of the dikes in the Netherlands. This research may contribute to the protection of the hinterland without the use of expensive interventions. In the process I learned a great deal about the loads caused by overtopping waves, but even more about the strength of the soil and in particular the strength of the grass sod. This last subject is generally not part of a study in Hydraulic Engineering, but turns out to be an important aspect in the safety against flooding.

I would like to express my gratitude to my supervisors from INFRAM Gosse Jan Steendam and Roy Mom for their guidance, feedback and time to help me with the topic. I also would like to thank Gerben Van der Meer (Van der Meer Innovations) and the members of the Department Flood Defence of INFRAM, in particular Jan Bakker, for their help performing the sod pulling tests and their knowledge into this topic. Special gratitude is reserved for Gijs Hoffmans from Deltares who helped me throughout my thesis to obtain insight into the behaviour of a grass sod. I hope this thesis will help them with their on-going research into this topic. Furthermore, I would like to thank my graduation committee consisting of the following members:

Prof. dr. ir. S.N. Jonkman	Chairman of the Committee, TU Delft, department of Hydraulic Engineering
Prof. dr. ir. J.W. Van der Meer	TU Delft, department of Hydraulic Engineering, Unesco IHE and principal of Van der Meer Consulting bv
Ir. H.J. Verhagen	TU Delft, department of Hydraulic Engineering
Ir. G.J. Steendam	INFRAM, Head of Department Flood Defence
Ir. R.J.C. Mom	INFRAM, advisor Department Flood Defence

In addition to the people who have supervised or guided me during my thesis I would also like to thank my family, friends, team mates, roommates and colleagues who have supported me not only during the execution of this thesis, but also during my years at the TU Delft.

Last but not least a special thanks to my parents for their continuing support throughout my time at the TU Delft.

I hope you will enjoy reading this master thesis!

Delft, May 21, 2015,

Roel Bijlard

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List of symbols

In the following table the list of symbols is ordered alphabetically, with their explanation and units.

Symbol	Explanation	Unit
a	Scale factor to normalize Weibull distribution	-
A	Cross sectional area	m^2
A_0	Area of the grass sod	m^2
A_1	Area of 1 m^2	m^2
A_b	Area of the bottom plane of the sod	m^2
A_r	Area of roots of number of roots per m^2	m^2
A_r/A_1	Root Area Ratio (RAR)	-
A_s	Area of one side of the sod	m^2
b	Shape factor for the extreme tail in Weibull distribution	-
B1	Boonweg 1 (location)	-
B2	Boonweg 2 (location)	-
B3	Boonweg 3 (location)	-
B4	Boonweg 4 (location)	-
c	Cohesion	N/m^2
C	Chézy coefficient	$m^{1/2}/s$
C_{clay}	Rupture strength of clay	N/m^2
C_V	Coefficient of variation	%
d	Diameter	m
dF	Increase in shear force at obstacle	N
D	Damage factor in Cumulative Overload Method	m^2/s^2
E	Modulus of Elasticity (or Young's Modulus)	N/mm^2
F	Shear force under flow conditions on regular slope	N
F_2	Measured maximum force condition 2 test	N
F_4	Measured maximum force condition 4 test	N
F_c	Critical frictional force	N
F_i	Maximum force to extract an intact sod	N
F_p	Maximum lift force	N
F_M	Maximum shear force under flow conditions	N
F_{max}	Maximum measured force	N
F_t	Critical mean tensile force on bottom element	N
F_w	Submerged weight of the soil	N
g	Gravitational acceleration	m/s^2
h	Maximum flow depth at crest of dike	m
H_s	Significant wave height	m
k_0	Depth averaged turbulent kinetic energy	m^2/s^2
l	Length scale	m
L_0	Thickness of grass sod	m
L_{op}	Wavelength in deep water with corresponding peak period T_p	m
M	Millingen aan de Rijn (location)	-
n	Porosity	-
N_W	Number of incident waves	-
N_{OW}	Number of overtopping waves	-
p_m	Maximum lowering of local pressure caused by eddies	N/m^2
p_w	Pore water pressure	N/m^2
P_V	Probability of individual wave will be less than a given volume	-
$P_{V\%}$	Percentage of wave volumes exceeding a given volume	%
q	Mean wave overtopping discharge	$m^3/s/m$

r_0		Depth averaged relative turbulence intensity	-
R_c		Relative crest freeboard	m
R_h		Hydraulic radius	m
RAR		Root Area Ratio	‰
S_b		Dike slope	°
t		(Storm) Duration	s
t_{sr}		Maximum load duration	s
T_m		Mean wave period	s
T_{ovt}		Wave overtopping duration	s
T_p		Peak period of incoming wave	s
u		Maximum flow velocity of overtopping wave	m/s
u_*		Bed shear velocity	m/s
U		Velocity	m/s
U_c		Critical velocity	m/s
U_0		Depth averaged velocity	m/s
v_r		Load parameter for overtopping and run-up waves	m/s
V		Volume of a wave	m^3
z		Depth below surface	m
z_q		wave run-up height associated with a run-up discharge of 0.1 l/m/s on an infinite long slope	m

α	1.	Dimensionless factor	-
	2.	Slope angle	°
	3.	Shape factor	-
	4.	Acceleration factor	-
$α_M$		Load factor	-
$α_S$		Strength factor	-
Γ		Mathematical gamma function	-
Δl		Displacement of the sod	mm
$ε$		Relative deformation	-
θ	1.	Angle of shear rotation	°
	2.	Steepness of the slope	°
$λ_{ref}$		Reference height	m
μ		Average value	-
ρ		Density of water	kg/m^3
$ρ_s$		Density of the soil	kg/m^3
σ	1.	Normal stress	N/m^2
	2.	Standard deviation	-
τ		Shear stress	N/m^2
ϕ		Angle of internal friction	°
Ψ		Shields parameter	-

Frequently used subscripts and notations

Many subscripts will be used multiple times in this thesis. In order to keep the list of symbols organized, the subscripts below can be applicable to every symbol from the previous table. The subscripts are grouped together with similar implication.

Subscript		Explanation
c		Critical value
e		Effective value
U		Velocity related
0	1.	Initial value
	2.	Depth averaged
clay		Of the clay
grass		Of the grass
r		Of the roots
s		Of the soil
h		Horizontal component
v		Vertical component
x		In x-direction
y		In y-direction
z		In z-direction

Furthermore there is a frequently used notation, which may be placed after the symbols (with subscript).

Notation	Explanation
(0)	Located near surface level

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1   Introduction

1.1   Research background

There is a shift in the approach for designing coastal structures. In the previous years dikes were designed on the probability of exceedance of an incoming wave during storm conditions. There were different storm probabilities in the Netherlands varying from 1 in 1.250 years to 1 in 10.000 years. In the near future, the design criterion will become the probability of flooding of the hinterland. In order to determine this flooding probability, the strength of the dike has to be known. Also the governing failure criterion of a dike needs to be established in order to design the dikes in such a way that they are strong enough to resist the storm conditions. It is important to determine the difference between a safe design and possible failure of the dike, in terms of strength and crest height.

The current state of the dikes in the Netherlands is not always sufficient to resist the future water levels and wave loads acting on it. In order to protect the hinterland from flooding, the crest heights of the dike may need to be raised. However, raising the crest has a major impact on the immediate vicinity of the dike: elevating dikes will result in loss of land as the base of the dike will subsequently have to be widened as well, in order to provide stability for the dike as a whole. This lost land at the landward side of the dike is often occupied by buildings, agricultural lands or nature. Besides the loss of land, raising the crest is also a costly procedure. Therefore it is essential to look into other options for protecting the hinterland from flooding.

Dikes in the Netherlands often have a similar structure (see Figure 3). The core of the dike is generally made of sand but can also be constructed of clay. On top of the core is a cover layer of clay of at least 0.7 metre thickness. On the seaward side the clay layer is usually 1 to 1.5 metres thick. The top of the cover layer is a grass revetment on the landward side. The top of the seaward side is also covered with grass, whereas the lower part has a stone revetment in order to withstand the breaking waves.
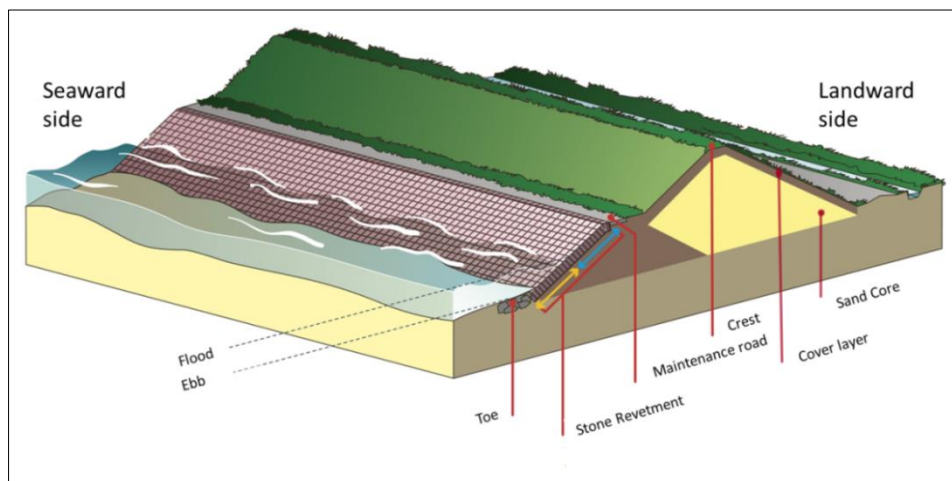
Figure 3 - Structure of a common dike in the Netherlands (Project Bureau Zeeweringen)

A severe storm can damage the structure of a dike in three stages. An incident wave first collapses on the hard covered revetment on the seaward slope of the dike. After the wave is broken the water will run-up over the seaward grassed slope of the dike. The run-up that comes over the crest towards the landward (grassed) slope is considered an overtopping wave. The run-up that does not reach the crest height will run back down towards the sea as shown in Figure 4 (Schüttrumpf, 2005 and Van der Meer, 2014). Wave run-up and wave overtopping are comparable in behaviour, in both cases there is

a wave front running over the slope. The difference is that during wave overtopping the front velocity of the wave is increasing (depending on the slope angle), where it is decreasing with wave run-up. Wave impact during breaking of the waves has a different load mechanism and is not comparable with wave overtopping and run-up.
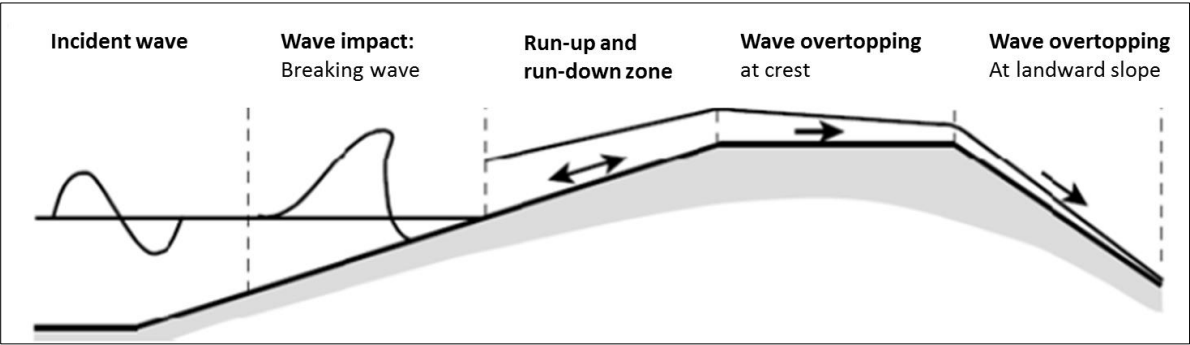
Figure 4 - Process of wave breaking, run-up and wave overtopping at a dike (Van der Meer 2014)

The overtopping water can erode the cover layer of the dike after which the sand core will be washed away. When this core erosion starts, the dike will fail soon after, leading to flooding of the hinterland. The governing strength of the dike is in the grass layer, which provides most resistance against the overtopping water.

To prevent failure of the dike, it is an option to raise the crest of the dike, but there are other possibilities to ensure the dike stability. If the dike can resist a certain amount of overtopping water without leading to failure of the dike, the crest does not need to be elevated. Nowadays almost no wave overtopping over the crest of the dike is allowed. The current regulations allow for a wave overtopping volume of 0.1 to 1 litre per second per running metre. Figure 5 shows the crest freeboard as a function of the average wave overtopping discharge for three different wave heights (Rijkswaterstaat, 2012). The left part of the graph shows that a small increase in the average wave overtopping discharge leads to a large decrease in crest height. This influence becomes smaller after the allowable average wave overtopping discharge becomes higher than 10 l/s per metre. This is because the graph is on a logarithmic scale: there is an equal crest difference between 0.1 and 1, as between 1 and 10 and between 10 and 100 l/s per metre. To conclude, a small increase in the allowable average wave overtopping discharge (between 0.1 and 10 l/s per metre) has a large influence on crest freeboard and consequently on the total dike height.
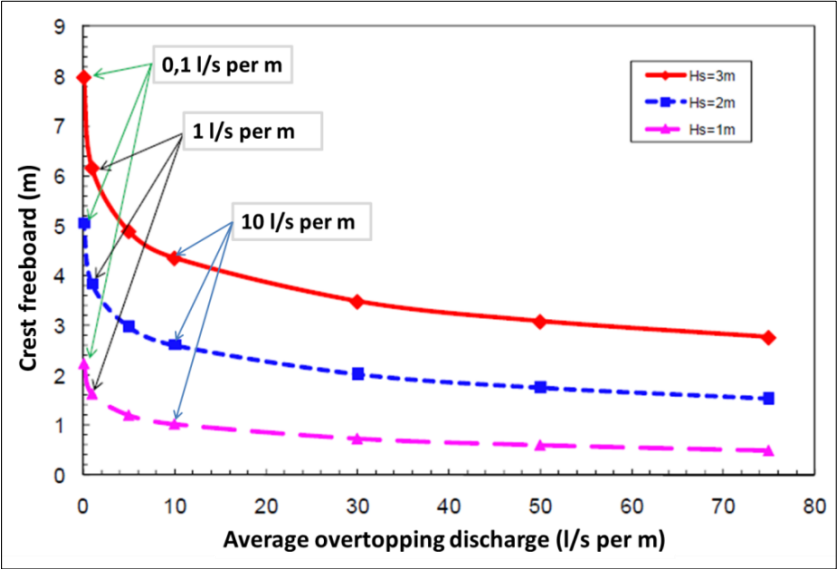
Figure 5 - Relation between crest freeboard and the average wave overtopping discharge for three different wave heights (Rijkswaterstaat 2012)

In the past few years a great deal of research has been done into estimating the allowable wave overtopping before erosion of the landward slope starts and the stability of the dike is undermined. During some of these tests, real dikes are tested in situ with a wave overtopping simulator. This is a simulator which generates waves at the crest of the dike, which then flow over the landward side of the dike. The results from these tests show that the allowable wave overtopping discharge can be higher at certain locations than the current regulations dictate. A grass revetment can withstand large overtopping waves for quite some time, provided the grass is in a good condition.

To allow a certain amount of wave overtopping volume, the strength of the dike and in particular the strength of the grass sod has to be known. The present tests of checking the strength of the grass are either time consuming or not directly related to the governing strength. Therefore, a new method to test the strength of the grass sod has been developed i.e. the sod pulling test. However, it requires additional research to find out how the results of this test can be optimized and used as input for a new way to determine the allowable wave overtopping volume.

Furthermore there is a shift in the definition of the critical wave overtopping criteria. Until now the mean wave overtopping discharge is the governing parameter. A problem with this criterion is that waves with a large volume and velocity do not have a bigger impact on the erosion of the grass layer than the smaller waves. In reality however, larger waves contribute most towards the erosional process and smaller waves have less impact on the erosion.

Another problem with the average wave overtopping discharge is that there is no difference in wave climate. A river dike has a lot of small overtopping waves, whereas a sea dike has only a couple of big overtopping waves. With the current method they can have the same average wave overtopping discharge. A new method has been developed to account for larger waves to generate more impact. This new method is called the Cumulative Overload Method, which uses the front velocity of the overtopping wave (which is a load parameter) and the critical velocity (which is a strength parameter) of the grass sod as the representative parameters for the strength of the grass sod on dikes during wave overtopping.

1.2   Research objective

In this master thesis the relation between the strength of the grass sod and the erosion of this sod during overtopping wave conditions will be studied. This leads to the following research question:

"Can the results from the sod pulling test be used to determine the critical velocity of grassed slopes on dikes in the Netherlands during wave overtopping conditions?"

To provide an answer for this question, two topics have been distinguished: the strength of the grass sod and the critical velocity of the sod.

1.2.1   Research steps

In order to answer the research question, several steps have been defined for the two topics. First the strength of the grass sod will be investigated, based on the following goals:
- Describe the structure of a grass sod on dikes in the Netherlands
- Investigate the current methods of determining the grass strength on dikes
- Describe the sod pulling test and compare it with the current methods available
- Investigate different influences on the measured strength of the grass sod with the results of the sod pulling test
- Develop a methodology to calculate the strength of an intact grass sod from the results of the sod pulling test
- Investigate different grass sod properties related to the strength of the sod

The goals for determining the critical velocity of the grass sod are:
- Describe the Cumulative Overload Method
- Investigate the critical velocity formula and its relation with the sod pulling test

1.3 Limitations

Certain limitations are set in this thesis for reasons of efficiency.
1. Only the erodibility of the grass sod is taken into account; erosion of the clay layer and core of the dike are neglected. Furthermore, piping, (micro and macro) stability and other failure mechanisms of the dike are not included in the analyses;
2. The landward side of the dike is studied, therefore wave overtopping is the load factor;
3. Wave run-up and wave impact occur at the seaward side of the slope and are therefore both disregarded.
4. The strength (α_S) and load factor (α_M) in the Cumulative Overload Method will not be used in the analyses of this research.

1.4 Research approach

The content of the research is dominated by the sod pulling tests performed during this thesis. The data analyses from these tests are elaborated in order to get a better understanding of the behaviour of grass and the sod pulling tests. In addition, the Cumulative Overload Method and its components will be discussed, where the focus will be on the critical velocity. This thesis can be divided in four main parts.

1.4.1 Part I – Current knowledge of grassed slopes

In part one of this thesis the current knowledge about grass on dikes is studied. This part will give an elaboration on the properties of the grass sod and on the current methods for determining the strength of grass. Here the focus of the current methods will be on the advantages and disadvantages of each method. This part ends with an explanation of the sod pulling test and the improvements made over the past two years.

1.4.2 Part II – Data analyses of the sod pulling tests

Part two of this thesis is based on the sod pulling tests performed in this research. In total 158 tests have been performed in order to gather more insight into the behaviour of grass under a certain imposed elevation. Different grass sod conditions are tested in order to investigate numerous strength influences. For instance, the frame size and the saturation conditions have been changed during the tests. During all tests the force and displacement were measured over time and will be used in the analyses. An important chapter in the second part is the conversion from the measured strength during the sod pulling tests into a critical grass normal stress, which can be used as a strength indicator of the grass sod during wave overtopping.

1.4.3 Part III – Critical velocity of grassed slopes

In the third part of this thesis the Cumulative Overload Method is studied together with the effect of overtopping waves on a dike section. In this method the critical velocity has an important role, therefore this parameter is discussed in detail. The strength of the grass determined in the previous part, is used as input in the critical velocity formula. At the end of part III all the previous chapters will be combined in order to find an answer to the main research question.

1.4.4 Part IV – Conclusion and recommendation

The last part of this thesis consists of an elaborated summary of the conclusions drawn from the previous chapters. This will be followed by some recommendations for further research into the topic of the strength of the grass sod on dikes during wave overtopping.

PART I -

CURRENT KNOWLEDGE ON GRASSED SLOPES

2 Grass covers in the Netherlands

The cover of a dike consists of a clay cover protecting the dike core. On the top of the clay layer a grass cover is laid out. Grass is one of the most prevalent types of surface protection on dikes in the Netherlands. Its primary function is the protection of the dike body against erosion induced by loads from waves and currents. Therefore a grass cover should be erosion resistant. This attribute is mostly gained from the interaction between the soil and the root system of the grass.

A grass layer can be compared with reinforced concrete. The concrete is used to take up the pressure force, the same as the clay layer. The grass sod is comparable in function with the reinforced steel; they give the structure some resistance against pulling forces. In this chapter the composition of the grass sod will be discussed followed by the properties of the clay layer underneath it.

2.1 Composition of grass

The resistance against erosion of a grass cover comes mainly from the structure of the root system and not from the leaves and stems above the ground (Burger, 1984). There are additional factors that influence the strength, like the coverage of the grass, the seepage or surface irregularities. A grass sod is proven to be an elastic-plastic material, which can deform centimetres without tearing. In Figure 6 a grass cover with its definitions is shown (TAW, 1997).
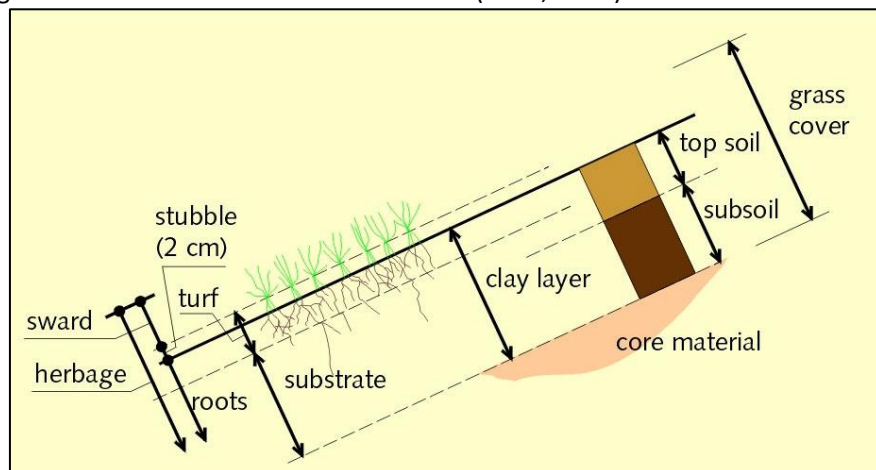
Figure 6 - Structure and layout of a grass cover (TAW 1997)

Sward and stubble are the green grass parts that are visible above the ground. Herbage consists of the sward and stubble and the roots under the ground level. In the top clay layer, most of the roots are found and provide most of the resistance against the erosion. The number of roots declines exponentially over the depth, so the strength of the grass cover is mainly in the top layer. The vertical structure of the sod, with its resistance against erosion, can be schematised as follows for a well rooted sod (TAW, 1997).

- The uppermost layer of 1 to 35 mm consists of loose soil and plant remains. This layer is washed away quickly by waves.
- Immediately below there is a layer of 5 to 50 mm thick in which the sod is loosely packed and closely rooted. This layer provides high resistance against erosion and is slowly eroding away.
- Under this layer is a 5 to 15 cm thick layer in which the sod is more closely packed, but with considerably less roots. This zone is still quite erosion resistant against overtopping waves.
- Further below, the number of roots decreases further and the soil is more closely packed, leading to less resistance against wave overtopping conditions.
- Below the last layer will be the core of the dike, consisting of clay or sand, which provides hardly any resistance against erosion.

The grass cover should be sufficiently closed to provide support against erosion.

However, this vertical structure can show substantial differences over short distances. The horizontal structure of these vertical zones differs significantly over a few metres. This is due to the local heterogeneity and interaction between the plant roots and small animals.

The grass cover consists of small and large particles, pores and roots. The smaller clay particles can group together, which creates aggregates of several centimetres. This will be explained in the next paragraph. A network of roots is often densely packed where the roots act as anchor to keep soil particles together. The aggregates are kept together by very fine root hairs and symbiotic fungal threads in the soil. Large particles are held together by the coarser roots in the top layer. This network of fine and coarse roots lead to a strong, flexible and permeable grass sod. Furthermore, the sward and stubble of the grass cover protect the roots from the direct impact of the flow.
Without the anchoring effect of the roots, individual particles are easily washed away during storm conditions. When loads are acting on the sod, the weakest roots will break first, but the force will be redistributed to other roots. This will weaken the sod slightly until the displacement of the sod reaches critical values. Then the redistribution stops and the sod will fail.

The grass sod is subjected to various influences which determine the strength of the layer. These influences can be divided into two groups, natural and man-made influences. Examples of natural influences are the caves and tunnels dug by mice and moles. Man-made examples are wheel tracks due to mowing and hay-making, fences and stairs on the slope for visitors, etc. These factors damage the grass sod which results in weak spots on the slope with less resistance against wave overtopping.

The structure and strength of a grass cover is also influenced by the different seasons of a year. The grass is stronger in the summer months compared to the winter months. The regenerative ability of the sod is also higher in the summer; small damages in the sod are more quickly repaired to its original state. When looking at the root density (see Chapter 3.1.3), there is a factor 0.5 difference in the grass quality between the different seasons (Alterra, 2014). This difference is quite large, therefore the governing conditions of a dike depend on the period when the maximum loads are expected. For sea dikes, the storm conditions in the winter months will be decisive, whereas the highest loads on river dikes can occur year round. It is important to determine the strength of the grass sod under the right conditions.

In this thesis the terms "grass sod", "sod", "grass cover" and "grass layer" are interchangeable. These four terms represent the grass cover shown in Figure 6. The sward and stubble are normally not considered, since their influence is limited. The exact strength of the grass will be examined later on in this thesis. The purpose of this part is mainly to provide a general insight into the structure of the top layer.

2.2   Properties of clay

The behaviour of the grass sod is discussed in the previous section, now a further elaboration will be given on the properties of the clay in the top layer. Clay has large influence on the strength of the sod due to the suction pressures in the top layer. The focus in this part is on providing insight into the effect of saturation on the strength of the top layer. In order to understand this influence, first a short introduction about the clay cover layer.

2.2.1   Introduction

In the years following the construction of the cover layers, the clay will have a developed soil structure. This development is caused by different factors such as dehydration in the sunlight, moisture from the rain, expansion resulting from frost, digging of small fauna, worm holes and roots penetrating the soil and extracting moisture. This soil structure is more distinct in fine grained soil than in sandy soil.

One of the consequences of the soil structure is a large increase in permeability of the clay. This increase in permeability is typically larger in vertical direction than in the horizontal direction. A problem with this structured clay is that it cracks when it dries up. This can cause damage to the roots and the contact areas between the aggregates. Examples of cracked clay are shown in Figure 7. The structure development has also effect on the shear strength of the soil.

Figure 7 - Examples of cracked clay due to drying of the soil

The grain size distribution and the Atterberg limits are important parameters for the soil structure development. The Atterberg limits are also used to determine the erosion resistance of clay. There are three different categories for clay: strong (C1), moderate (C2) and poor (C3) erosion resistant clay. Category 3 clay should not be used as a cover layer. The quality of the grass layer determines if category 1 or 2 should be used in the cover. Category 2 can be used if there is a strong grass system present on the slope. In Figure 8 the Atterberg diagram is shown, explaining the categories of clay (Rijkswaterstaat, 2012).
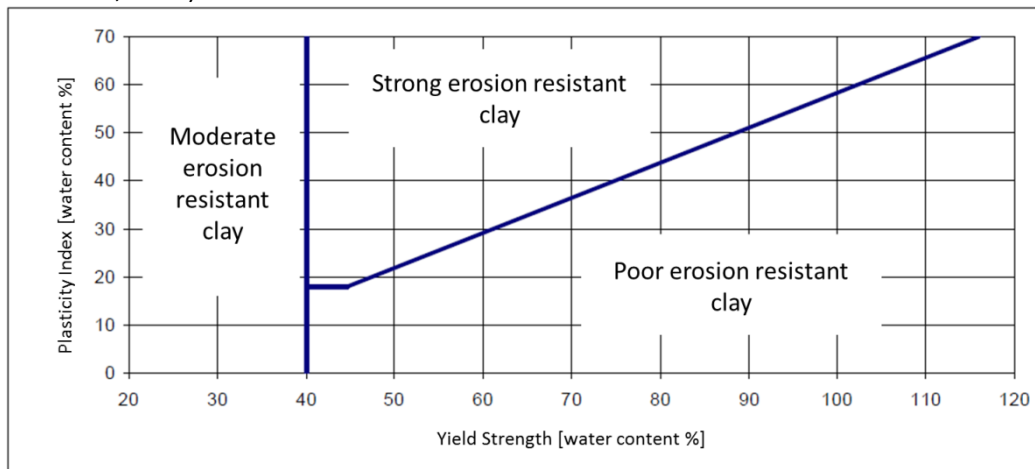
Figure 8 - Atterberg diagram showing the layout of erosion resistant clay, little erosion resistant clay and unsuitable soil (Rijkswaterstaat 2012)

The strength of a clay cover layer is mainly influenced by the size of the clay aggregates and the weaker zones between the aggregates. Compacted clay has a high resistance against erosion (+- 25 N/m^2) and a low hydraulic conductivity. However, structured soil has a higher hydraulic conductivity and a lower resistance against erosion (+- 2 N/m^2) than compacted clay (Hoffmans, 2012).

2.2.2 Suction pressure

Saturation of the soil affects the erodibility and the stability of the top layer, but the stability of a dike is not part of this thesis. However, since the erodibility of the top layer is also affected by the saturation, its influence will be discussed below. The suction pressure depends on the degree of saturation and has a positive influence on the strength of the sod during overtopping waves.

Above the water table the pores in the clay cover are usually not fully saturated. As a result, the pore pressure is thus negative compared to the atmospheric pressure. This under (or negative) pore water

pressure is called the suction pressure, as in this situation the clay can "suck up" water from the water table. The suction pressure keeps a thin layer of water around the aggregates. As more water is drained the layer grows thinner, leading to an increased suction pressure.

Pore water pressure can only become positive in the larger pores, when water percolates through these open spaces due to infiltration of outside water. The smaller pores inside the aggregates will still experience suction pressures, since water does not infiltrate quickly into the aggregates itself. As a result of the water overpressures, the water in the larger pores is attracted towards the pores in the aggregates. This leads to a slowly expanding aggregate. This process is shown in Figure 9 (Hoffmans, 2012).
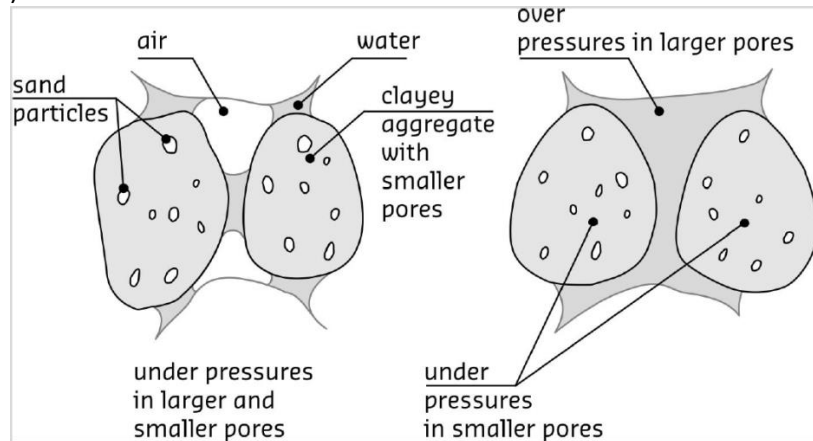
Figure 9 - Clayey aggregates before and after infiltration (Hoffmans 2012)

Evaporation (direct and through vegetation) into the atmosphere plays also an important role in the suction pressure. Among other factors, the rate of evaporation depends on the relative humidity of the air and the temperature. Precipitation and temperature changes can allow the suction pressure to vary greatly, for example if it rains in the summer it is less than 50 kN/m^2. But in dry summer conditions the pressure can have extreme values, up to 1000 kN/m^2. In winter conditions the suction pressure is usually below 10 kN/m^2 in the clay cover. When the ground is completely saturated the suction pressure is zero. The suction pressure has to be overcome first, before the grass sod can be lifted upwards. The higher the suction pressure, the higher the resistance is against the erosion of the sod.

2.2.3 Size of the suction pressure

Van Hoven *et al*. (2010) developed a new method to determine the suction pressures during wave overtopping. The method consists of three distinct steps:

1. Determine infiltration time [s]: Infiltration will only occur when there is a (thin) water layer on the surface. When water overtops the dike, it supplies a water layer for some time, after which it runs off. The slope will dry, unless a next wave overtops the dike sooner. The added time for which water is on the surface is called the infiltration time. There will be a water layer on the surface for an average of 30 seconds per overtopping wave. The infiltration time decreases with an increasing slope angle. When waves overtop the crest with an interval less than 30 seconds, the slope will stay wet, leading to a high infiltration time.

2. Determine the infiltration capacity [m^3/s per m^2]: The infiltration capacity of the slope surface determines the amount of water which can infiltrate the cover layer. The infiltration capacity of structured clay covers in the Netherlands is in the order of 1x10^{-5} and 1x10^{-4} m^3/s per m^2. The infiltration capacity can be determined by pushing a steel tube into the slope to the depth of the end of the cover layer. The tube is filled with a known value of water. The decrease of volume over time is equal to the infiltration capacity.

3. Determine the potential pore pressure build-up [m^3 per m^2]: When the steps 1 and 2 are multiplied by each other, it results in the infiltrating volume. This infiltration volume must be compared with the volume of the larger pores, in order to determine if full saturation of the cover layer is reached. The volume of the larger pores is a safe estimate in the order of 0.125 m^3 per m^2. This value can also be determined by laboratory testing on large soil samples. The soil structure development depends on a lot of factors, but research within the framework of TAW 1997 led to a fairly general soil structure build up. This is shown in Table 2. Using the values in this table leads to low estimate of macro pores of 60 litres and a high estimate of 120 litres per m^2.

Table 2 - Clay aggregates description over the depth of the cover layer (Van Hoven, 2010)

Depth (m)	Aggregates discription	*Macro pores*
0.00 – 0.05	Very small and loose, kept together by roots	> 30%
0.05 – 0.20	0.1 – 3 cm, loosely packed	20 – 30 %
0.20 – 0.40	3 – 6 cm, loose fit	5 – 20 %
0.40 – 0.80	5 – 15 cm elongated, tight fit	2 – 5 %
> 0.8	Vertical cracks	< 2 %

2.3   Erosion of a grass cover during wave overtopping

In this section only a short introduction into the erosion of the grass sod during wave overtopping will be given. A further elaboration into these processes will be given in Chapter 8.

Wave overtopping on a grassed inner slope is caused by incoming waves which are of such height that they flow over the crest of the dike. The hydraulic parameters that determine the wave overtopping are the governing wave conditions and the geometry of the dike. These parameters can be divided in wave height, wave period, wave steepness, storm duration and the relative crest freeboard.
The wave overtopping itself can be described by a number of parameters. The most used description is the average wave overtopping discharge, which is equal to the amount of water in a storm overtopping the crest, divided by the duration of the storm. Commonly used average overtopping discharges in the Netherlands are 0.1; 1 and 10 l / s per m of width. In reality, irregular waves hit the embankment and all overtopping wave brings a certain amount of water along with it. Important parameters here are the distribution of overtopping wave volumes and the progress of the velocity and water layer thickness during the overtopping wave.

The first erosion generally starts on a local weak spot or on a section with a locally stronger water flow. Ground particles will erode and flushed away with the overtopping wave. This process has a strong probabilistic behaviour. The erosion is will then continue to increase by a combination of two factors: Concentration of the flow and acceleration of the (supercritical flowing) water.

There are multiple stages of erosion during wave overtopping. Most of them will expand in downward direction of the slope after initial damage. Only with head cut erosion, the erosion will also expand upward. The different stages of erosion are (see SBW 2007):

1. *Erosion of loose material*
   Immediately during the first overtopping waves, loosely packed material will be washed away. Examples of loose material are hay, loose grass, semi and fully decomposed organic material and small litter. Furthermore, as a result of the flowing water, the grass will be pressed flat on the slope. This leads to a visually different slope, but it does not lead to increased erosion.

2. *Erosion of the grass sod*
   At the moment bald spots are formed and bare clay appears at the surface, erosion of the grass sod has started. There are different types of grass erosion: Washing away of the soil particles at the surface, loosening of the grass sod and disappearing of the grass cover by rolling down or bulging. The bare clay which is now visible at the surface still has cohesion due to the rooting in the clay layer.

3. *Erosion of the clay layer*
   The erosion of the clay layer will expand slowly by wearing of the top of the clay layer. This will eventually lead to deep erosion holes with steep walls in the clay layer and increasing erosion rate by breaking of the clay.

4. *Head cut erosion*
   Erosion of the clay layer can be followed by head cut erosion, which occurs when the upstream slope is almost vertical and therefore geotechnical instable. Lumps of clay can collapse into the erosion hole. This stage of erosion will be accelerated when the core of sand is reached. This sand will rapidly wash away from the upstream side of the hole, which further undermines the covering clay layer stability. When this stage is reached, the dike has failed and soon a breach in the dike will be formed.

For the prediction of the erosion of the cover layer, several hydraulic and soil related parameters are defined.

- Hydraulic parameters: Water layer thickness (h), maximum flow velocity (U_{max}), relative turbulence intensity (r_0) and the duration of the load (t)
- Soil related parameters: Thickness of the sod (L_0), shear strength of the grass sod (τ_{grass}) and the clay (τ_{clay}), the size of the clay aggregates (d_a), density of the sod (ρ_s) and the parameter C_E.

From all these parameters is the factor C_E the most unknown. This parameter can be estimated based on a qualitative description of the grass sod quality and the quality of the clay, see Chapter 3.

3 Methods for determining the grass strength

As grass is the most frequently used dike protection in the Netherlands, it is important to be able to measure how strong the grass sod is. Different factors influence this strength, for example orientation of the slope, fresh or salt water environment and the type of maintenance of the grass layer. Many different methods to determine the strength of the sod exist. One of the main problems with these methods is that they only give an estimation of the strength which is based on an indirect relation.

Older methods used in the past will be discussed in Section 3.1. Paragraph 3.2 shows how the classification resulting from these methods were used to determine the strength of the dike during wave overtopping. Section 3.3 will discuss some new methods which are currently still under investigation. The chapter will end with a discussion of the available methods and their disadvantages.

3.1 Methods used in the past

In the past the impression was that herbs had a positive influence on the strength of the grass sod. The herbs have bigger and stronger roots and thus provide higher resistance against the erosion compared to regular grass. So the grass covers in the Netherlands were maintained to have as much herbs as possible. The methods for determining the strength of the sod were also based on this assumption, where the strength of the grass layer was divided in 4 categories: Good, moderate, poor and very poor. With these qualifications a number of parameters were estimated, which could be used in calculations. The three methods in the past for determining the strength of the grass sod were:

1. By means of visual inspection, there are two ways:
    a. Determining the sod quality by maintenance type;
    b. Determining the sod quality by composition and coverage
2. By inspection of the rooting of the grass layer

Firstly, the visual inspections will be discussed, which start by determining the quality of the sod by looking at the type of maintenance. After that the strength will be determined by looking at the composition and coverage. Lastly, the rooting will be the governing factor in determining the quality of the sod.

3.1.1 Maintenance type

The strength of the grass sod is strongly dependent on the way the grass is maintained. To prevent the grass and herbs to overgrow the normal condition, minor maintenance is needed regularly. This can consist of grazing, hay-making and/or mowing.

The type of maintenance influences the sod and root density of the grass. For a strong grass cover a sufficiently closed and well rooted grass cover is required. There are four main classifications of maintenance, which are subdivided by the amount of fertilizer used (Nitrogen) and the type of maintenance. The resulting classification from this method can be used as an estimation of the grass cover quality. The four classifications (A, B, C, D) of maintenance are given in Table 3 (Rijkswaterstaat, 2012). They are subdivided into these different classifications because they serve different purposes.

- Classification A is associated with hydraulic engineering. It results in an erosion resistant grass layer on top of the dike.
- Classification B is used for extensive agricultural management. Due to the fertilization and grazing, this leads to moderate erosion resistant grass.
- Classification C is used for intensive agricultural management. The grass layer is not erosion resistant, so its resistance has to come from the clay layer underneath the sod.
- Classification D is not suitable for water retaining dikes. The grass layer is not erosion resistant. This type of maintenance on dikes should be avoided at all times.

Table 3 - Sod quality as function of maintenance type (Rijkswaterstaat, 2012)

Type of Maintenance	Some characteristics of the sod		Sod Quality
	Sod Density	**Sod Penetration**	
Hay-making without fertilization (A)	Covering >70%	Many thick and thin roots in 0-15 cm layer	Good
	Open patches <2 cm^2		
Grazing with max. 75 kg N/ha fertilization (B)	Covering >85%	Many thin roots in 0-8 cm layer	Good
	Open patches <2 cm^2		
Lawn management (mowing 7-8 times a year), no fertilization (B)	Covering >85%	Many thin roots in 0-5 cm layer	Moderate
	Open patches 2-5 cm^2		
Grazing with 75-100 kg N/ha fertilization (C)	Covering >85%	Many thin roots in 0-5 cm layer	Moderate
	Open patches 2-5 cm^2		
Grazing with >100 kg N/ha fertilization (C)	Covering >85%	Few thin and some thick roots in 0-5 cm layer	Poor
	Open patches >5 cm^2		

3.1.2 Composition and coverage

When there is no clear maintenance type of the dike section or the estimated quality associated with that maintenance is doubtful, the quality of the sod can be determined by the composition of the vegetation. Every vegetation type has its own characteristic species .These species are strongly linked to the maintenance type. During visual inspection, attention is also being paid to rough grown species, saline plants, percentage of herbs and moss and traces of moles and mice. When an inventory of the observed species has been made, the quality of the grass layer can be checked by the coverage and if needed upgraded with the root density. This estimation of the sod quality is made in Table 4 (Rijkswaterstaat, 2012).

Table 4 - Sod quality as function of vegetation type (Rijkswaterstaat, 2012)

Vegetation Type	Maintenance Type	Sod Coverage	Root Density	Sod Quality
Pioneer vegetation				
P: Species pioneer community (<4 years)	D	Moderate/Poor	Poor	Poor
Meadow				
M1: Few species in meadow	D/C	Good	Poor	Poor
M2: Moderate species in meadow	B	Good	Moderate	Moderate
M3: Many species in meadow	A	Moderate	Good	Good
Hayland				
R: Rough hayland	D	Very poor	Poor	Very Poor
H1: Few species in hayland	D	Poor	Poor	Poor
H2: Moderate species in hayland	B	Moderate	Moderate	Moderate
H3: Many species in hayland	A	Moderate	Good	Good

The columns of sod coverage and root density in this table can be used for indication. For below categories the sod coverage has influence on the sod quality in this estimation.

- For M2 and H2:
  - Coverage >70%, the sod quality is moderate
  - Coverage <70%, the sod quality is poor.
- For M3 and H3:
  - Coverage >70%, the sod quality is moderate
  - Coverage <70%, the sod quality is poor

3.1.3 Rooting

The two methods described above give a first estimation of the grass sod quality. When there is still doubt about a certain sod quality, the rooting of the sod can be established. The rooting, which is indicative of the strength, also relates to the vegetation and maintenance type. However, it is possible that the previous methods under- or overestimate the sod quality. In order to determine the rooting, the root density of the grass sod has to be determined.

A soil-drill with a diameter of 3 cm is used to dig up 4 soil samples up to 20 cm depth. These samples are cut into pieces of 2.5 cm each. The number of roots larger than 1 cm in every piece of the sample (0-5) is counted. This number is then used to categorize the root density into 6 groups as shown in Table 5. When at each depth the category score is determined, Figure 10 can be used to establish the sod quality (VTV, 2006).

Table 5 - Categorizing the root density over the depth

Category	Root Density
0	No roots
1	1 - 5 roots
2	6 - 10 roots
3	11 - 20 roots
4	21 - 40 roots
5	> 40 roots
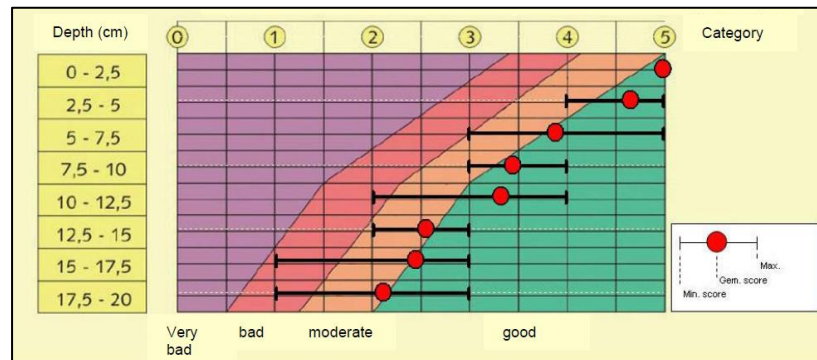
Figure 10 - Sod quality as function of root density (VTV 2006)

The average of the 4 samples is taken to determine the area in which the sod is qualified. In most cases the dots will be in the same coloured area, so the quality is easily determined. However, it is possible that the root density categories are not all in one coloured area. When two or more points are outside a given area, the lowest score over this soil sample is taken. In the figure above the resulting sod quality is good.

3.2 Result of previous methods

When the sod quality was determined by one of the above methods, Figure 11 (VTV, 2006) could be used to determine if the quality of the sod could withstand the loads caused by the waves. In this figure the maximum load duration is given on the horizontal axis (t_{sr}) and the load parameter (v_r) on the vertical axis. The coloured lines give the maximum load as a function of the time, in order to get a "good" score of the dike section. The maximum permissible load duration for a score to pass is given by the coloured area ("voldoende" in Figure 11). When the point of load and time is to the right and above the given area, the score is insufficient, so the dike section does not pass the test.

A good score can only be given if the sand content in the clay is below the 50%. For a sufficient score the sand content should be between the 50% and 70%.
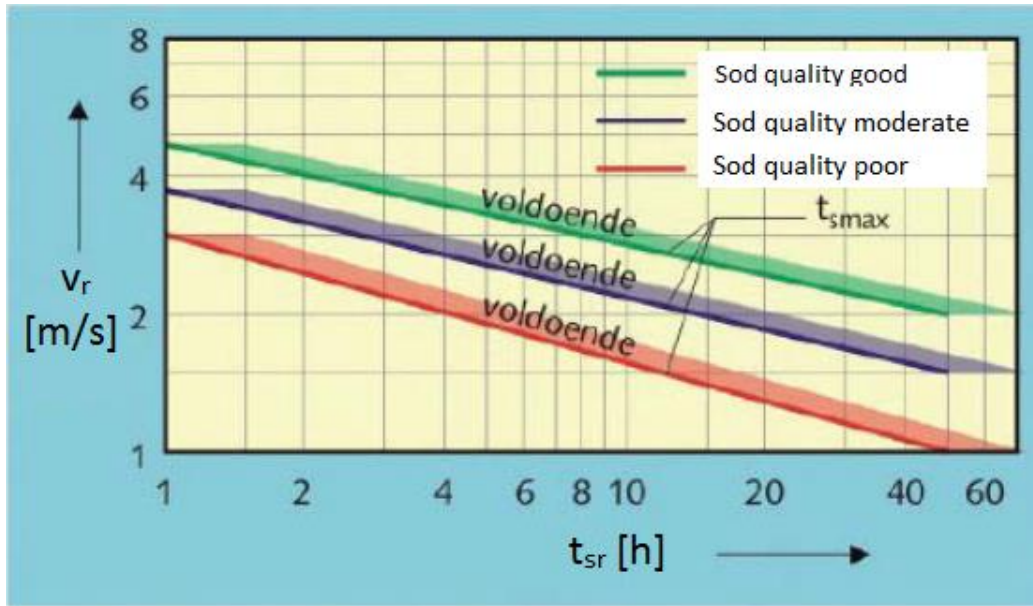
Figure 11 - Detailed calculation method to review the erosion by wave run-up and overtopping (VTV 2006)

The load parameter is a value for the wave run-up velocity, which is exceeded by 2% of the incoming waves. The value is calculated by Equation 1.

$$v_r = 700 \frac{H_s}{T_p} \left(0.085 - \frac{H_s}{L_{0p}} \right) \left(1 - \frac{z}{z_q} \right)^{0.5} \tan \alpha_0 \qquad (1)$$

In this equation is z the height of the point on the slope, z_q is the wave run-up height associated with a run-up discharge of 0.1 l/m/s on an infinite long slope, H_s is the significant wave height, L_{op} is the wavelength in deep water with corresponding peak period T_p and α_0 the average slope angle.

The calculated value of v_r is also used for the overtopping waves on the inner slope.

3.3   New methods

In the previous sections the older methods used in the past are discussed. Nowadays new testing methods are under development, since the older methods do not always provide the correct estimated strength. For example, the wave overtopping simulations showed that the influence of the maintenance type on the strength of the grass sod not always in accordance with the theory from Paragraph 3.1.1. This is partly because the influence of the roots from herbs provides less resistance against erosion than expected. Also the roots from the grass provide more strength than previously expected.

With the past methods the grass sod quality was divided into four categories: Very poor, poor, moderate and good. In the latest reports a shift is made from these four towards three categories in which the density of the root system is governing. The three new categories are: Closed grass sod, open grass sod and fragmented grass sod. With this new breakdown, two methods are available to determine the strength of the sod: a visual inspection and a simple field test (Rijkswaterstaat, 2012).

- Visual inspection: The three categories can be determined by visual inspection. Here the coverage of a recently mowed slope is estimated. This is done with the representative spacing between plants. This is an overall estimation of the distance between the hatched places of different plants.
- Simple field test: When there is some doubt in the visual inspection of a certain area a simple field test can be performed to test the strength of the sod. At a representative location and homogeneous part of the slope, a sample of 0.25 x 0.30 cm is cut out of the soil with a spade. The sod with a thickness of about 70-100 mm is lifted and tested.

With these two tests, the quality of the grass sod can be divided into the three new categories:

1. Closed grass sod: A closed and densely rooted grass sod in which no visual disruptions are present in the sod larger than 0.20 metre in length. The representative spacing is less than 0.1 metre which also must be smaller than 10 per cent of the area up to 0.20 metres. No more than 2 locally damaged areas (0.15 x 0.15 m^2) are allowed per square metre.
   During the cutting for a field test the sample remains largely intact when loosening it from the subsoil. When the part is cut out, it requires some pulling effort (with bare hands) to separate the soil sample into smaller pieces.

2. Open grass sod: An open rooted grass sod, which has local compactions in a widely woven root system. The representative spacing is less than 0.1 metre, which must be smaller than 25 per cent of the area up to 0.25 metres. No more than 2 locally damaged areas (0.15 x 0.15 m^2) are allowed per square metre.
   During the field test it is only with necessary caution possible to collect an intact soil sample. The sample falls apart when applying a minor pulling force.

3. Fragmented grass sod: A fragmented rooted sod in which there are a few local compactions in a further widely woven root system. The representative spacing is more than 25 per cent of the area and larger than 0.25 metres. The root layers are often over more than 20 cm substantially (or completely) absent. It is not possible to gather an intact soil sample for the field test.

Another method is currently under development by Alterra. With this method soil samples of 20 cm thick and diameter of 5 cm are taken. The samples are divided in slices of 2.5 cm thick and all the roots are taken out carefully. When all the ground has been removed, the roots are tested in two different ways.

1. The roots of one slice are placed in a Flat Bed Scanner. This scanner measures the total root length and classifies the length of different diameter roots in different groups. This gives a good overview on the type of roots in the system.
2. A number of roots (not the biggest, not the smallest) are taken from the samples and tested for their tensile strength. The breaking force and extension will be measured, along with the diameter of the root. This information is used to estimate the strength of the sod.

This is a more elaborate method than the older method of root density. Since this method is still under development, there are no conclusions available yet with the results of these tests.

3.4 Discussion

Each of the above mentioned methods has one or more disadvantages for determining the strength of grass during overtopping. Some disadvantages are common while others only occur during certain methods. The older methods are discussed first.

The maintenance type chosen for a particular grass sod should result in a species rich mixture, which was assumed to have a high resistance against erosion. But when the strength of the dike is purely based on the type of maintenance, it gives an overall estimation purely on the basis of this specific type of maintenance. It does not take into account current state of the dike, the local weak spots, vegetation types, orientation, etc. For instance when a grass cover is facing north, moss growth is to be expected. This moss may have a negative effect on the strength of the sod, because they do not grow roots. This can lead to a different strength than the maintenance type assumes.

When looking at the composition and coverage some problems of the previous method are covered. But the coverage and local weak spots are still not really taken into account. Only in certain cases, when the coverage is below 70%, it influences the outcome of the test. It is still highly correlated with the type of maintenance, so will generally come to the same conclusions.

During the testing of the root density the number of roots inside the sample larger than 1 cm is counted. However, no distinction is made between the different kind of roots, like horizontal or

vertical, grass roots or roots from herbs, different diameters, etc. The number of roots is not always the determining factor. A few big roots for example may give more support than numerous smaller roots. Furthermore, it is possible to have different classifications at different depths, which influence the overall class and so under- or overestimate the governing strength against erosion.

Some big disadvantages occur in all the old tests, but are also still present in the newly developed methods. Three main points are:

1. All the methods use certain characteristics that influence the strength of the sod, but there is no method available with a direct link with the strength against erosion.
   The new method currently under development by Alterra measures the length and diameter of all the roots in a sample after which some of the roots are tested for their individual strength. However, it does not directly relate to the strength of the roots in the grass sod, since the roots are in a system where they do not work independently from one another. It is not easy to match the results of the test with the reaction of the roots when applying a pulling force on the grass sod. Furthermore, the influence of the clay in which the roots are rooted is neglected. They do make an estimation of the coverage of the grass sod, in order to determine possible weak spots.

2. All the methods categorize the sod quality into 3 or 4 categories, which give insight in the approximated strength. But since there is no clear transition in nature, there will always be sections which are close to the boundaries of that category. With these categories it does not show how strong the good quality grass layer exactly is.

3. All methods give a general overall strength, where local weak spots are neglected if there are not too many of them. During wave overtopping however it is established that the weaker areas can start the erosion process of the dike section. The weak spot will slowly expand at first but will increase faster and faster into an erosion hole with all its consequences. However, it is hard to indicate the spots on the slope which will erode first during the wave overtopping simulations. The weakest spots are not always visible before testing.

The problem with the Figure 11 for determining the final score of the dike section is that there is one figure for wave run-up and overtopping. The processes are quite similar in behaviour, but there is a difference between them. During run-up the wave speed will slow down on the slope, where for overtopping waves the front velocity increases over the slope as a function of the slope angle. Furthermore, the inaccuracies of the methods described above will influence the end result in the figure, which can under- or overestimate the strength of the dike section.

The current methods and there disadvantages are explained in this chapter. The newly developed sod pulling test which will be investigated in this thesis will be covered in general in the next Chapter.

4   Sod pulling test

4.1   Introduction

Two years ago INFRAM was asked by Deltares to develop a machine to test the strength of a grass sod. Jan Bakker and Gerben van der Meer started developing the sod pulling test. It was quite a struggle to find an easy method that gives decent results. A simple method is preferred because the future plan is to let dike managers use it to test the strength of the grass sod on dikes. When this method is accepted, dike managers can put the equipment in the trunk of their car and test some particular dike sections for their strength.

Various possible ways of testing the sod strength have been investigated, which could represent the resistance during wave overtopping. One of these methods was inserting circular forks into the sod, which grasp the sod from all directions. The sod puling test was eventually chosen because it was easier to handle and cheaper. This method is based on a technique were the vertical uplifting force is the governing parameter, which is also the case for the erodibility of a grass layer during wave overtopping.

4.2   Method

The test set-up of the sod pulling test consists of a small pull frame (see Figure 12), which is pulled up by a hydraulic cylinder and a manually operated hydraulic pump. The cylinder is placed in a supporting frame, which is placed directly above the small pull frame (see Figure 13). The tensile forces and deformations are recorded as a function of time by applying a force measuring sensor and a displacement meter.

Figure 12 - Small pull frame which anchors the sod

Figure 13 - Overview of the sod pulling device

In order to place the pull frame, the soil has to be excavated on two opposite sides up to 8 cm depth. Three to four pins are inserted below the surface of the grass through the soil in the frame. The number of pins depends on the number of sides cut. The pins should not grasp the sod near a cut edge because tearing the pin through the sod becomes more probable.

The sod pulling test has certain degrees of freedom in sod conditions and testing. First of all, there is a difference in the test conditions during pulling. The tests are performed with two sides of the sod cut and two sides intact (condition 2 test) and with all four sides cut loose (condition 4 test). The sod during a condition 4 test is shown in the Figure 14. With this last test the sides do not contribute to the measured strength during lifting of the sod, only the bottom of the sod resists against the uplifting force.

Figure 14 - Top view of the condition 4 test with all sides cut

Since at least two sides of the sod have to be excavated, it is impossible to test the strength of the complete sod with four sides intact. Grass has roughly the same strength in all directions on the same depth, therefore the condition 2 and 4 test methods are correlated. When the difference between the condition 2 and 4 tests is known, it can result in an estimation of the strength when the sod is still intact. However, a problem with this method is that it is impossible to test the same grass sod twice. Since grass has a strong heterogeneity, there can be a large difference in the measured forces. Therefore some problems still have to be investigated in order to use this method for determining the strength of the grass sod.

There are also two different ways of testing the strength: rapid tests and fatigue tests. For the rapid tests, the tensile force is increased until all roots have failed. This test is performed by slowly increasing the elevation of the sod, which induces resistance against this motion by the roots. Failure of the roots means that the roots have snapped or that they are pulled out of the underlying soil.

For the fatigue test the same grass sod is put under tensile stress repeatedly in order to see how the grass behaves under multiple loads. Each repetition in itself should not be large enough to break the grass sod, but due to the many repetitions the sod can fail eventually. There are two types of fatigue tests possible with this machine. For the first one the grass sod is pulled up with an imposed tensile force. For this force the 75% of the breaking force of the rapid tests can be applied. After the sod is pulled up the tensile force is reduced to zero. These steps are repeated 100 times or until the sod has failed. The second type of fatigue test is by imposing increasing displacements (and releasing it to original position) on the grass sod. Every displacement is repeated ten times, so 10 x 5 mm displacement, followed by 10 x 10 mm, etc.

The sod conditions can also be a variable during testing. The ground is not completely saturated under normal, but during storms (which can result in overtopping waves) the ground will become more and more saturated over time. In order to mimic the conditions during wave overtopping as much as possible, the ground should be saturated for some time before testing begins. However, it is interesting to investigate how large the influence of saturation is.

4.3   Improvements
Since the start of this project a lot of improvements have already been made. The most important improvements are listed below.
- The first few tests were performed with a manually operated hydraulic pump, which required a pulling up and down motion of a lever. A consequence of this motion was that there was fluctuating force on the sod. The lever is replaced with a wheel, which can be operated more smoothly. However it still is a manually operated system. This is chosen because of the fact that there is no electricity on most parts of a dike and the system should be easy to operate.

- At the beginning the force on the grass sod was measured by means of the oil pressure in the hydraulic cylinder. After some tests it became clear that there was a difference in the measured force with this method and the force measuring sensor. The difference was around 25%, so definitely not negligible. This difference can be explained by three things:
    - The friction in the hydraulic hose between the cylinder and the pump; this friction is not constant per load.
    - The dead weight of the cylinder was not taken into account.
    - The capacity of the pump is much bigger than the force needed for the sod pulling test, therefore the measurements are less accurate compared to using the pump full potential.

  The oil pressure measurements are not used anymore; the force is now measured with a digital tension gauge. This however does not record the data. So the maximum force has to be read manually. Therefore there is no progress of the force in time, only the maximum can be used for analyses. It is possible to gather additional data with equipment from Deltares, where a data logger stores the data from a force measuring sensor and a displacement meter. Both measure the progress four times every second.

- When a sod is pulled out of the ground, pictures are taken and estimations of the thickness are made which can be used in the analyses. The thickness can differ quite a lot over the different tests. With some tests the sod is sheared at the depth of the pins, but the plane of shear can also be around 10 cm depth. When pictures are taken, it is always possible to check for anomalies in the sod when looking at the data. With the tests of 2 sides still intact also the width of the sod sample can be measured.

But since the test is still developing itself, not everything has been taken into account. Some areas do need extra attention whether it is the best possible way of testing.

1. The frame size used for testing needs further research. The area of 15 by 15 cm is chosen, because it is the area where damage starts to develop during the tests with the wave overtopping simulator. It is also the representative size of a clump of grass poll. But is this indeed the optimal size for the sod pulling test?

2. Under which soil conditions should the test be performed? Due to possible suction pressure between the aggregates the saturation of the soil has an influence on the strength of the grass sod. So should the sod pulling test be performed during normal conditions or when the ground is completely saturated and what is the difference between them?

3. How should the sod pulling test be performed? Is the rapid test preferable to one of the fatigue test or is it the other way around? Or are they all needed in order to determine the strength of the grass sod?

These questions are a big part of the fourth research goal in this thesis. They are only mentioned in this section, a further elaboration on these subjects will follow in Chapter 5 to 7.

There are also some problems with this testing technique that still need to be solved.

4. The main problem is how to use the results from the sod pulling test to calculate the critical velocity in the Cumulative Overload Method. Is it possible to link the results from the test to the critical velocity formula? Since this is the research question, this will be dealt with later on in this thesis.

5. Another problem is how to cope with the difference in sizes between the testing area and the determined critical velocity of an entire dike section. Is it possible to find the weakest spot on the dike and use this value as the minimum? Or is the distribution of the strength a useful tool and for example the 5% tail value the governing parameter? The spread is partly due to the inhomogeneity of a grass sod, but how to deal with this?

PART II -

DATA ANALYSES OF THE SOD PULLING TESTS

5   Results of the sod pulling tests

5.1   Introduction

For the research in this thesis additional sod pulling tests are performed in Millingen aan de Rijn (Gelderland, Netherlands) and at the Boonweg near Sint Jacobiparochie (Friesland, Netherlands). The exact locations can be found in Appendix A. These tests are executed in the last 2 weeks of September 2014. During these tests different variables are examined for their influence on the strength of the grass sod. All these different kinds of tests and their purpose are further explained in Section 5.2. Then there are some general remarks made, which are applicable for all the tests. This chapter ends with a first analyses of the data gathered during the tests.

5.2   Test set-up

There are in total 158 pull-out tests performed during this research in order to investigate different influences. During these tests some variations in the testing methods will be used in order to compare the outcomes and check the influence of these parameters. This is all done in order to get a better understanding of what is happening to the grass sod when inducing a vertical displacement. An overview of the different test variables is given below.

5.2.1   Location

The additional tests are performed at five locations in the Netherlands for specific reasons. At these locations wave overtopping simulations have been performed in the past. Since the main question of this thesis is to find a link with the strength during wave overtopping, it is important to test at such locations. The first location is along a river dike of the Rhine, near Millingen aan de Rijn. This dike section is facing North East and the intruding water was fresh.

The other locations are at the Boonweg near Sint Jacobiparochie, which is a south facing sea dike in the north of the Netherlands, protecting the Netherlands from the Wadden Sea. Four different maintenance types on the dike are implemented here over the last 25 years in close proximity of each other. The different types of maintenance resulted in different structure of the grass sod and so in a different strength. Since the maintenance is the only altered factor influencing the sod in these sections, the influence of the type of maintenance can be investigated. The outcome of these tests can be compared with the theoretical strength of the different types of maintenance (see Chapter 3.1.1) to check whether they give the same results. The exact location of the 4 test sections is shown in Appendix A1 and A2.

The different maintenances types at the Boonweg and Millingen are:

Boonweg 1   Periodic grazing with low sheep intensity, with 70kg N/ha fertilization;

Boonweg 2   Twice intensive grazing, one time hay-making, no fertilization;

Boonweg 3   No grazing, twice hay-making, no fertilization;

Boonweg 4   First haymaking, then grazing, followed by an extra hay-making, no fertilization;

Millingen   No grazing, twice hay-making, no fertilization.

These maintenance types should result in the following strengths, according to Chapter 3.1.1.

- Boonweg 3 and Millingen (H3: Many species in Hay-land): Good quality grass
- Boonweg 1, 2 and 4 (M2: Moderate species in Meadow): Moderate quality grass

5.2.2   Frame size

Since the sod pulling test is a newly developed method of testing, there are still some questions about the optimal way of testing, as discussed in Chapter 4.3. Some improvements have already been made, but some areas do require extra attention. First of all, the size of the tested grass sod can be optimized. In the existing datasets, most tests are performed with a testing frame of 15 by 15 centimetres. Also some tests are performed in Wageningen with a frame size of 10 by 10 cm. This was done because there was a test section with small areas of all kind of different compositions of grass and herbs. The 15x15 frame size was too large for testing these small sods, therefore this

smaller frame size was used there. But since grass is heterogeneous, the idea is that the bigger the tested area the smaller the scatter in the results. In a larger area the local variations are of less importance in the outcome, everything is averaged out on a larger scale. However, the frame size cannot be increased infinitely, because the whole testing system has to remain workable. Therefore it is chosen to develop a larger frame of 20 by 20 centimetres in order to investigate the relation between the tested area and the scatter in the results. The 10 by 10 frame size will also be used at Millingen aan de Rijn for comparison with the other sizes. This size is less constant and is more affected by the cuts made at the sides, so it gives less accurate results. Because of this, the 10 by 10 frame size will not be used at the Boonweg.

5.2.3 Rapid and fatigue test

During storm conditions multiple waves will overtop the crest of the dike. It is likely that the dike will not fail after one wave, but reduces in strength per overtopping wave. This can be explained by the fatigue of the grass sod and the redistribution of forces (see Chapter 2.1). Therefore it is important to investigate the influence of fatigue on the strength of the grass sod.

There are two different methods with the sod pulling device for the fatigue tests. The first one is by imposing a constant force and repeating this for 100 repetitions. It is assumed that applying 75% of the maximum force will lead to failure after 100 repetitions (Hoffmans, 2012). The results from these tests can lead to a fatigue curve, which can be compared with other fatigue curves of wood like materials. However, a problem with this method is that it is impossible to exactly determine the 75% value. An estimation can be made from the rapid tests performed at that same testing location, but due to the scatter of the data, this estimation is not very precise. It can happen that the sod fails after the first repetition, without even reaching the 75% value (it was much weaker than expected) or will not fail after more than 100 repetitions (it was much stronger than expected). A lot of fatigue tests need to be performed in order to find spots that are usable for analyses for the applied imposed force. Fatigue tests are time consuming, therefore this testing method is not implemented.

The second fatigue testing method is by imposing a constantly increasing displacement. In this case the sod will always fail during the tests, but the number of repetitions depends on the maximum displacements that this sod can withstand. Every imposed displacement is repeated 10 times, after which the displacement is increased by 5 millimetres. This sequence is repeated until the measured force is only a fraction of the maximum force, after which the sod is pulled out. A problem with this method is that this is not in accordance with the accepted theory of fatigue. So a different formulation of fatigue might need to be formulated in order to use these results. Since the influence of fatigue is not the main focus point in this research, the second method of testing the fatigue is chosen for a first impression of this influence.

5.2.4 Additional tests

The normal tests consist of at least five condition 2 and five condition 4 tests for the different frame sizes per location. The fatigue tests are done according to the condition 4 test in order to reduce the time span of these tests. However, there are some extra tests performed to investigate different influences on the grass strength. These can be ascribed to the saturation (1), the strength of the clay (2), bricks underneath the grass sod (3) and the influence of the sides in fatigue tests (4). Since these are additional tests, they are not done at every location, so there are fewer results available for the data analyses. Therefore all the extra tests are performed with the 15x15 frame size in combination with the condition 2 method, in order to keep the most parameters constant. This will give some insight into these influences on the strength of the sod.

1. It is interesting to investigate the influence of saturation on the strength of the grass sod. To simulate the sod conditions during wave overtopping, the ground has to be saturated for approximately 2 hours. This results in lower suction pressures in the ground and therefore in a lower resistance against the uplifting force. How big this influence in reality will be is not clear yet. To investigate this, additional tests will be performed on unsaturated sections of a dike. These results will be compared with the tests under saturated conditions.

2. The strength of the clay layer underneath the grass sod is not well known. When a lump of grass and clay from the top layer is eroded away, the layer underneath this sod is exposed to the overtopping wave. In this zone there are still some roots present, which give extra support to the clay layer. The strength of the remaining clay layer will be tested at 6 and 10 centimetres depth.

3. At the Boonweg, there are bricks present at the toe of the dike. These bricks were part of an old path on the dike. However, during the last expansion of the dike these bricks were not removed before elevating the dike. There is a clay layer of approximately 10 centimetres depth above the bricks, which is covered by grass. It is important to check whether these bricks are beneficial for the resistance against erosion or that it weakens the toe even more, because the roots of the grass cannot reach the deeper clay layers. When the grass is eroded, the bricks provide almost no resistance against the overtopping wave. The mowing of the toe is difficult due to the transition from slope to berm, which decreases the strength of the toe even further. So it is interesting to test the differences in strength at the toe and at the slope of the dike.

   There are also bricks present at the fences, which separate the different sections of a dike. These bricks are placed as reinforcement of the dike near these fences. So some tests are also done here in order to check the resistance of the grass sod against erosion.

4. There are multiple fatigue tests performed with 2 sides still intact. This is done in order to compare the differences between condition 2 and 4 fatigue tests and to investigate if this difference is comparable to the rapid tests.

5.2.5 Overview

In the above paragraph different variations of tests are discussed. In this section an overview is given of all the tests performed at the different locations. There are in total 158 tests performed for further research, which are distributed among several test methods, see Table 6 for the summary of these tests and Table 7 show more elaborate information about the tests per location. The experiment numbers indicate the tests in the database for this type of testing method. The numbers are randomly distributed over the tested dike section. These numbers are sometimes present in the legend of the graphs, to serve as identification of the corresponding test.

Table 6 – Summary of all sod pulling tests during this thesis

Test	Frame size	Number of tests	Remark
Condition 2	10x10	6	
Condition 4	10x10	6	
Condition 4	10x10	2	Fatigue tests
Condition 2	15x15	26	
Condition 4	15x15	26	
Condition 2	15x15	4	Fatigue tests
Condition 4	15x15	10	Fatigue tests
Condition 2	20x20	26	
Condition 4	20x20	26	
Condition 4	20x20	10	Fatigue tests
Condition 2	15x15	7	Unsaturated conditions
Condition 2	15x15	3	At the toe
Condition 2	15x15	4	Clay tests
Condition 2	15x15	2	Near the fence

Table 7 – Detailed overview of all tests per location

Location	Test		Frame size	Number of tests	Experiment numbers	Remark
Millingen aan de Rijn	Condition 2	10x10		6	7,15,16,33,35,36	
	Condition 4	10x10		6	18,37,38,39,40,42	
	Condition 4	10x10		2	23,41	Fatigue tests
	Condition 2	15x15		7	3,4,11,22,24,27,31	
	Condition 4	15x15		6	5,9,10,25,26,28	
	Condition 2	15x15		1	8	Fatigue tests
	Condition 4	15x15		1	12	Fatigue tests
	Condition 2	20x20		6	6,14,20,21,29,30	
	Condition 4	20x20		6	2,13,17,32,34,43	
	Condition 4	20x20		2	1,19	Fatigue tests
	Condition 2	15x15		4	1E,2E,3E,4E	Unsaturated conditions
Boonweg 1	Condition 2	15x15		5	1,4,5,17,18	
	Condition 4	15x15		5	2,14,15,16,19	
	Condition 4	15x15		2	6,7	Fatigue tests
	Condition 2	20x20		5	3,8,12,23,24	
	Condition 4	20x20		5	9,10,13,21,22	
	Condition 4	20x20		2	11,20	Fatigue tests
	Condition 2	15x15		3	1E,2E,3E	Unsaturated conditions
	Condition 2	15x15		4	1K,2K,3K,4K	Clay tests
Boonweg 2	Condition 2	15x15		5	18,20,21,22,23	
	Condition 4	15x15		5	13,14,15,17,19	
	Condition 4	15x15		2	12,16	Fatigue tests
	Condition 2	20x20		5	3,4,7,8,24	
	Condition 4	20x20		5	5,6,9,10,11	
	Condition 4	20x20		2	1,2	Fatigue tests
	Condition 2	15x15		3	T1,T2,T3	At the toe
	Condition 2	15x15		2	H1,H2	Near the fence
Boonweg 3	Condition 2	15x15		5	1,2,3,4,5	
	Condition 4	15x15		5	6,7,8,9,10	
	Condition 2	15x15		2	V1,V2	Fatigue tests
	Condition 4	15x15		2	11,12	Fatigue tests
	Condition 2	20x20		5	13,14,15,16,17	
	Condition 4	20x20		5	18,19,22,23,24	
	Condition 4	20x20		2	20,21	Fatigue tests
Boonweg 4	Condition 2	15x15		5	1,2,3,4,5	
	Condition 4	15x15		5	6,7,8,9,11	
	Condition 2	15x15		1	10	Fatigue tests
	Condition 4	15x15		2	12,13	Fatigue tests
	Condition 2	20x20		5	14,15,16,17,18	
	Condition 4	20x20		5	19,21,22,23,24	
	Condition 4	20x20		2	20,25	Fatigue tests

5.3 General points

In the upcoming chapters different conclusions are drawn from the data gathered during the tests. There is a distinction made between results which influence the strength of the grass sod (this chapter), methods to determine the strength of an intact sod (Chapter 6) and grass sod properties (Chapter 7). First two general points are made which are applicable to all the tests in these chapters.

5.3.1 Measurements

During testing, measurements are made with a tension gauge and additional equipment from Deltares. The gauger had to be read manually, after which the maximum occurring force was written down. The Deltares equipment however measured the force and displacement 4 times every second. These data were stored on a logger, which could not be read instantly. So for an indication during the tests the tension gauge was used. There is a small difference between the measured values of the two devices, which is further elaborated in Appendix B1. The data collected with the Deltares equipment haven been used for most calculations, because these data are expected to be more accurate and provide more insight in the process during the tests. This device was calibrated and validated before it was used during the tests. In Appendix B2 an overview is given of what can be done with the output from the Deltares equipment.

5.3.2 Heterogeneity of the sod

Due to heterogeneity of a grass cover the results of the same type of test can differ quite a lot from one another, even when the tests are performed in close proximity of each other. From the current testing methods can be concluded that the coverage and the amount of herbs have influence on the strength, therefore these factors are estimated per section before testing. A problem however is that even when the areas look visually the same, there can be a relative large difference in the maximum measured force. This discrepancy cannot be excluded from the tests, it is characteristic for grass. Because of this, the individual test results are not the most important data. All the data of the same test on the same location have been combined into an average value (μ), with a standard deviation (σ) and a corresponding coefficient of variation (C_V). When using the data this way, the local discrepancies are assumed to average out as much as possible. The coefficient of variation is the standard deviation divided by the average and is a factor for the spread of the data around the average.

Most sections use a graph as a summary for all the tests used in that section. In the graphs are smaller shapes present, which represent the individual tests. The larger circles are the averaged value of the tests at that location and the black line is the average value over all the locations. Different locations are characterized by their own colour in the graphs: Millingen (M) is shown in red, Boonweg 1 (B1) in yellow, Boonweg 2 (B2) in green, Boonweg 3 (B3) in blue and Boonweg 4 (B4) in purple.

5.4 Strength influences

As a first part of the data analysis of the tests performed in this research, the influence of different factors on the measured strength of the grass will be investigated. First the influence of the saturation on the grass strength will be examined, followed by the influence of the different frame sizes on the strength.

5.4.1 Influence saturation

Saturation can have an enormous impact on the measured strength of the grass sod. When the ground is unsaturated the grass sod will experience large suction pressures through the clay layer, see Chapter 2.2.2. These pressures have to be overcome first before the sod can be lifted out of the ground. But during storm conditions and overtopping waves the ground will become more and more saturated over time. To simulate the conditions during wave overtopping in the best possible way, the suction pressures should be minimal. Therefore for all the regular tests, the ground is artificially watered for two hours until the cracks in the sod are completely saturated. In a small time span it is

not possible to fully saturate the top layer due to the long infiltration time of the pores inside the aggregates. However, it will simulate the wave overtopping conditions quite well.

There are tests performed in Millingen and Boonweg 1, where the ground was not artificially watered. Therefore the ground was under unsaturated atmospheric conditions. A problem however is that the weather has a large influence on the occurring suction pressures. During the testing in Millingen the weather was sunny and there had not fallen any rain in the previous 2 weeks. This resulted in a hard and dry sod when no watering was applied. Figure 15 shows the data from the weather station in Deelen, located 30 km north of Millingen aan de Rijn.
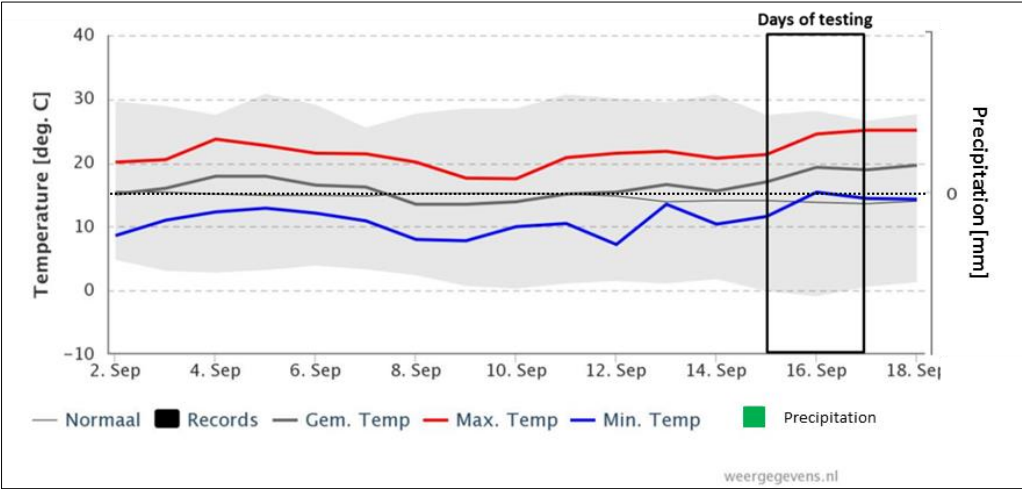
Figure 15 - Weather conditions near Millingen aan de Rijn up to two weeks before testing (Weergegevens.nl)

For the Boonweg, the weather station from Leeuwarden is used, located 15 km southeast of the Boonweg. Figure 16 shows that some rain had fallen in the week before testing. Also during the testing on Boonweg 1, some rain fell. The temperature was low and it was clouded. The day before testing Boonweg section 3, a large amount of rain had fallen in the area (approximately 40 mm at the test location). During the testing at Boonweg 3 and 4, the grass sod did not need much added water in order to become completely saturated; the sod was still soaked from the rainfall the day before.

Since the weather plays a factor in the outcome, the suction pressures for unsaturated tests in Millingen aan de Rijn are estimated to be larger than at the Boonweg, because of the lower degree of saturation.
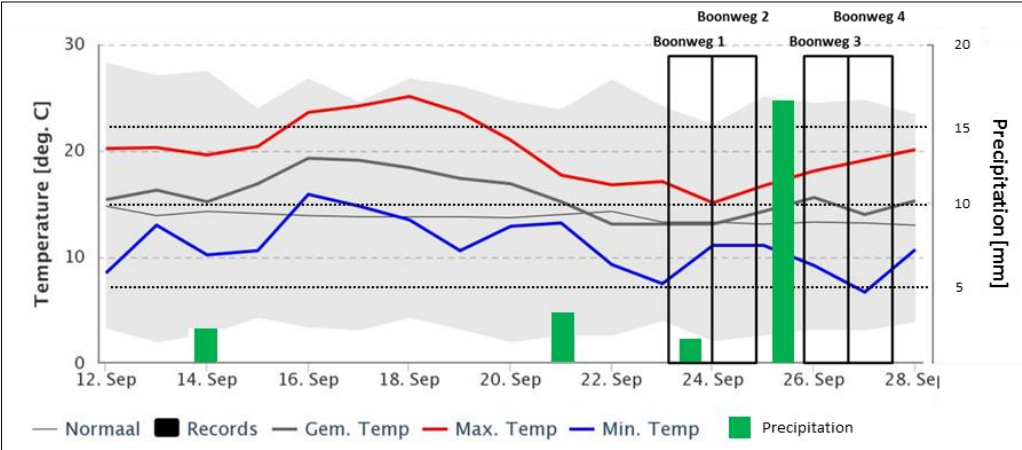
Figure 16 - Weather conditions near the Boonweg up to two weeks before testing (Weergegevens.nl)

Figure 17 show the results from Millingen and the Boonweg 1 for unsaturated conditions, which are compared with the same type of tests on that location for saturated soil.
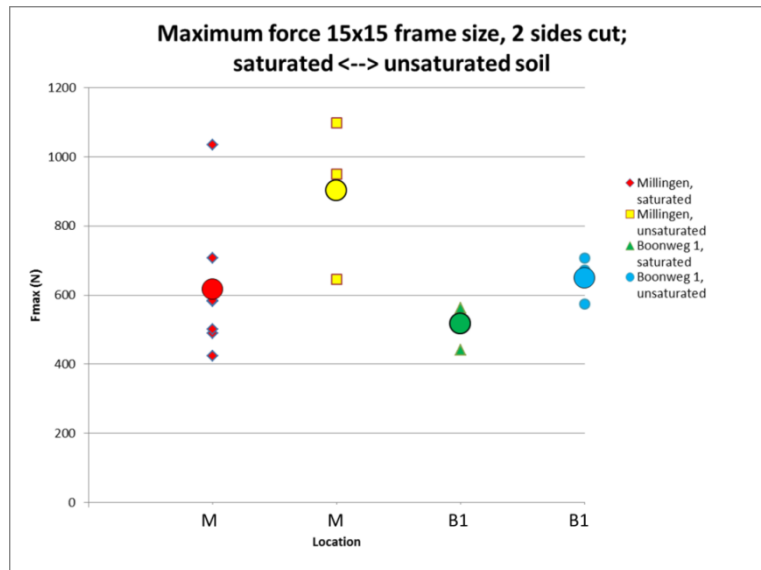
Figure 17 - Influence of the saturation on the measured force

For both test locations the different saturation conditions are averaged to one value and then compared to one another. From the graph it becomes clear that saturated soil provides on average less resistance against the uplifting of a grass sod. In Millingen aan de Rijn, where the ground was completely dry, this difference is on average a factor 1.4. The results from the Boonweg show the same pattern, but there is a smaller difference between the saturated and unsaturated conditions. This can be explained by the fact that it was clouded with a bit more saturation in the ground, which results in smaller suction pressures. But still there is a clear difference: on average a factor 1.25.

The weather has an influence on the results during testing. When testing on different days there will always be a deviation in the results due to changing weather. In order to simulate the conditions during wave overtopping, the soil should be completely saturated. So for testing in the right conditions the top layer needs to be watered for at least two hours or a reduction factor (1.0 - 1.4 depending on the weather conditions) in the measured forces must be applied when testing under unsaturated conditions.

5.4.2 Influence frame size

For the tests in Friesland and Millingen a new frame size is developed. This is done in order to check if an increased frame size leads to more constant results. When increasing the frame size, the local deviations due to the heterogeneity are divided over a larger area. So in order to get a more accurate result, the frame size should be as large as possible. It is however bound to a certain size, because of the practicability of the tests. So besides the 10x10 and 15x15 frame size, a frame size of 20x20 cm is developed. This section tries to see how the coefficient of variation (σ/μ) of the measured force behaves under these different frame sizes. In Table 8 the coefficient of variation of the measured forces is given per location. Only the regular tests are shown here since these are the most common and have the most data points per section. Each coefficient of variation is based on at least 5 tests.

In earlier research by Hoffmans (2014) it is mentioned that a good grass revetment has a coefficient of variation of about 20%. When there are tracks or irregularities visible in the grass layer, the coefficient can reach values up to 60%. A good grass layer can have the same order of heterogeneity as nearly uniform distributed sand, which has a coefficient of variation of 20 to 30%.

Table 8 - Coefficient of variation of the measured forces for different frame sizes

Frame size	Sides cut	Millingen	Boonweg 1	Boonweg 2	Boonweg 3	Boonweg 4	Average
10x10	2	31%					31%
	4	28%					28%
15x15	2	31%	8%	10%	11%	17%	15%
	4	14%	8%	14%	14%	20%	14%
20x20	2	19%	9%	14%	18%	10%	14%
	4	11%	19%	14%	12%	14%	14%

Since the 10x10 frame size tests are only performed in Millingen, there is no coefficient of variation available for the Boonweg locations with that frame size. For the 15x15 and 20x20 frame sizes all five locations are used to determine this coefficient. A lower coefficient of variation is the result of less scattered data, therefore a more homogeneous grass layer. From the 5 locations also the average coefficient of variation has been determined. All this combined should give insight in the scatter of results for the different frame sizes.

Conclusion

It can be seen from the table that the 10x10 frame size has a large coefficient of variation, which leads to a large scatter in the measured forces during the same type of tests. This is also in accordance with the theory, where smaller areas are more influenced by local deviations. Furthermore during testing of the 4 sides cut, it was noted that the sod was sometimes already pulled out of the top layer while removing the cutting frame. This means that the stickiness between the soil and the frame was enough to break the bottom roots and lift the sod up. There is also the influence of the cuts made, which disturb the ground and roots near these walls. When it is assumed that up to approximately two centimetres away from the cut the soil is disturbed, more than half of the area of testing is influenced during the condition 4 tests for the 10x10 frame size. These two influences occur with each test for every frame size, but because the forces needed to pull out a larger sod size are bigger the influence of this (pre)load is relatively smaller for bigger frame sizes.

Because this 10 by 10 frame size leads to less accurate results, it is not used anymore at the four locations of the Boonweg.

The table also shows that there is no clear difference in coefficient of variation of the 15x15 and 20x20 frame sizes. It is in the order of 15%, where it depends on the location whether the coefficient of variation of the 15x15 frame is larger or smaller compared to the 20x20 frame. It is however well within the range of the previous estimated 20% for a proper grass layer.

Discussion

There is no decrease in the coefficient of variation between the 15x15 and 20x20 frame sizes as was expected beforehand. But this can also be explained by the heterogeneity of the grass sod. Without increasing the frame sizes to unworkable sizes, the very local deviations can be spread over bigger areas, which decrease the coefficient. The problem is that grass is also not constant on a bigger spatial scale. Since the tests are about one metre apart from each other, possible spatial differences between these areas give different results. Spatial differences are for example more herbs or a different kind of herbs in the chosen sod. Furthermore also the coverage on a spatial scale can differ, which results in different amount of roots and so in a different strength. It is not possible to decrease the scatter of the measured forces further when randomly selecting the testing areas. When specific (and corresponding) types of visually the same grass sods are selected, it is possible to decrease the coefficient of variation. This is however not preferable, since wave overtopping is over the entire dike section and not over specific corresponding points on the slope. It might be interesting to look for weak spots in the sod and test those areas. A weaker spot is more likely to fail during wave overtopping, leading to more erosion around that area. This will be explained later on in this thesis.

6   Strength of an intact grass sod

With the current way of testing the grass sod is pulled up with 2 or 4 sides cut. But during wave overtopping the grass sod is still fully intact, where all sides are still connected so that there is an undisturbed grass layer. In order to determine the strength during wave overtopping, the strength of an intact grass sod needs to be known. There are two methods used for calculating the strength needed to pull out an intact sod. They are based on different principles (one practical and one more theoretical), where in both a certain factor plays an important role. It is convenient to express the strength of the grass sod in a critical mean normal stress, because this is independent of the frame size. Furthermore, the loads during wave overtopping are also often expressed in stresses so it makes an easy comparison with the strength.

In section 6.1 the practical method will be discussed, where in Section 6.2 the more theoretical method derived by Hoffmans will be investigated. Afterwards a comparison is made between both methods to check if they lead to the same results. This chapter will end with an empirical factor for determining the strength of an intact grass sod per test.

6.1   Practical method

The first method for determining the strength of an intact grass sod is based on the relation between the measured forces of the condition 2 and 4 tests. During the tests performed in thesis both condition 2 and 4 are tested, in order to find a correlation between these tests and the strength of an intact sod. When the minimum force required to pull out an intact sod has been determined, the tensile stress can be calculated by dividing it by the total area of the sod.

When 2 sides are cut during the testing, the other 2 sides and the bottom of the sod provide the support against the pulling force induced by the hydraulic cylinder. With the condition 4 tests, only the bottom provides this resistance. When both methods are combined the strength of an intact sod can be calculated. A problem however is that the sides are cut during testing, which influences the strength and the shape of the sod. Especially the corners of the sod area are influenced by this cutting. Therefore a shape factor is introduced, which will be explained in the next paragraph. The equation to calculate the intact sod is given by Equation 2.

$$F_i = \alpha * [F_2 + (F_2 - F_4)] \tag{2}$$

Where:

- F_i = Force needed to extract an intact sod [N]
- α = Shape factor [-]
- F_2 = Measured maximum force for two sides cut [N]
- F_4 = Measured maximum force for all sides cut [N]

When the force needed to pull out an intact grass sod is known, the tensile stress can be calculated by dividing it over the total area, see Equation 3.

$$\sigma_{grass,c} = \frac{F_i}{A_b + 4 * A_s} \tag{3}$$

Where

- $\sigma_{grass,c}$ = Critical mean grass normal stress [N/cm^2]
- A_b = Area of the bottom plane of the sod [cm^2]
- A_s = Area of one side of the sod [cm^2]

There are two different ways to use these equations. Per location at least 5 tests are done with the same frame size and sides cut. In order to use this data, a coupling of the data has to be made between the tests of same frame sizes but under different conditions (2 or 4). One can either use the averages of both tests to determine the strength of an intact sod for that frame size or match a F_2 test with a F_4 test. The last one can be done by arranging them on measured strength, where the largest F_2 force is matched with the largest F_4 force. This can be explained by the fact that a large F_2

force means that it was a locally stronger part of the grass layer, which means more horizontal and more vertical roots. The same holds true for the F_4 values, where a larger force correlates with more vertical roots.

When both methods are compared, they give the same average force for an intact sod. The only difference is the number of data points. Only one value will be available for analyses when the averages are used. When the tests are matched on value, there are 5 data points, which results in an average, a standard deviation and coefficient of variation. A benefit of this method is that not everything is averaged out. So when looking for the minimum (or maximum) value of the grass layer, this method is preferred. In Figure 18 all the original tests are given per location. On the vertical axis is the calculated critical mean grass normal stress plotted. There are four different kind of tests expressed as a critical mean normal stress for every location. These are the condition 2 and 4 tests for both the 15x15 centimetres and 20x20 centimetres frame size. On the horizontal axis each location has been plotted twice, where the left half shows the results of the condition 2 tests and the right half for the condition 4 test. The data points on the left per location represent the data from the 15x15 frame and the data points on the right the 20x20 frame size.

The data points of the 10x10 frame size are not plotted in the figure. The influence of the cutting of the sides is so large that it gives conflicting and inconclusive results. The condition 4 test is weakened too much by the four cut sides to give useable results. Especially when these tests are compared to the condition 2 tests of this frame size.
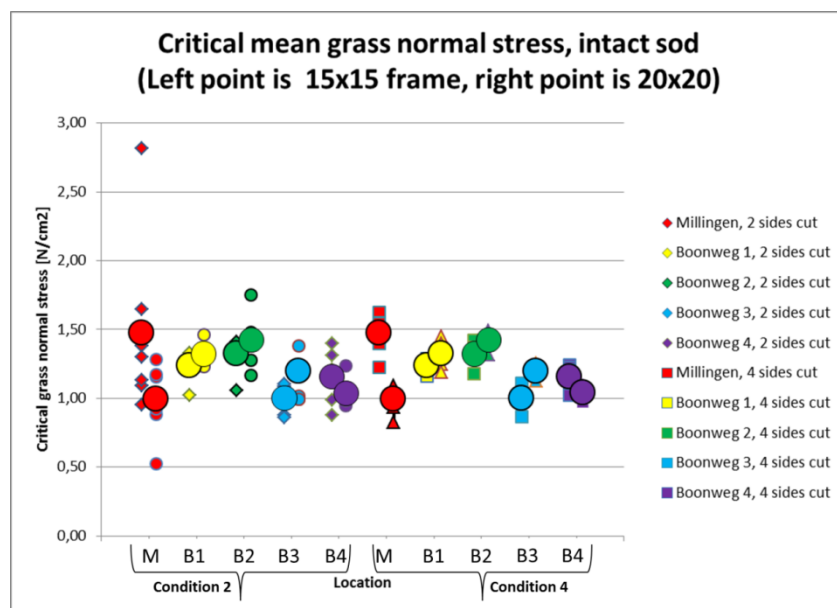
Figure 18 - Calculated critical stress for an intact sod with the practical method (results shown per location)

Conclusion and discussion

When the averages are used as a single data point, it is not possible to conclude anything about the scatter, maximum and minimum values. This could be important data in certain studies. Especially since the weaker sections are more likely to fail under overtopping waves. When the first real damage is formed at such a section, the erosion process is accelerated.

A problem with the method where both tests are sorted on value and compared is that the largest measured force for 2 sides cut accounts for a strong root system. But that does not mean that the largest measured condition 4 force had the same kind of root system. It could be possible that the highest condition 4 value, which should correlate with the condition 2 value, is not found (or the other way around). This causes the results of the intact sod to be over- or underestimated. However,

it still provides insight into the higher and lower values of the grass layer. The data point of 2.8 N/cm^2 in Millingen is an example of this problem. A high value for a condition 2 test was found for one area, but no matching condition 4 value was found, which results in a (too) high critical mean normal stress. For this reason the point will be neglected in further analyses.

6.1.1 Shape factor

The shape factor is introduced in the previous paragraph. Here follows the explanation and the size of this factor for the calculation of an intact sod.

When 2 sides are cut, the other 2 sides provide the remaining sod with extra resistance against the pulling force. This is the blue area in Figure 19, where all the areas of the pulled sod have been plotted in a 2-dimensional way. When Equation 2 from the previous paragraph is used without the shape factor ($F_i = F_2 + (F_2 - F_4)$), the red areas are added with the strength of the roots inside it. The corners of the sod are disturbed during the cutting of the sod, which results in less strength in these areas. This is not accounted for in the equation without a factor. When the basic principle is that the area of the sides has a linear relation with the resistance against the tensile stress, the green area has to be taken into account. This can also been seen in Figure 20, where the red circles indicate the corner areas which are reduced in thickness and so in strength.

The missing area on the sod can be related to a factor of the total area of the sod: the shape factor. When the frame sizes increases the total tested area increases and therefore the influence of the corners decreases. Table 9 shows the shape factors which have been used for calculating the strength of an intact sod for the different frame sizes. This factor has a linear relation with the maximum resistance of the intact grass sod.
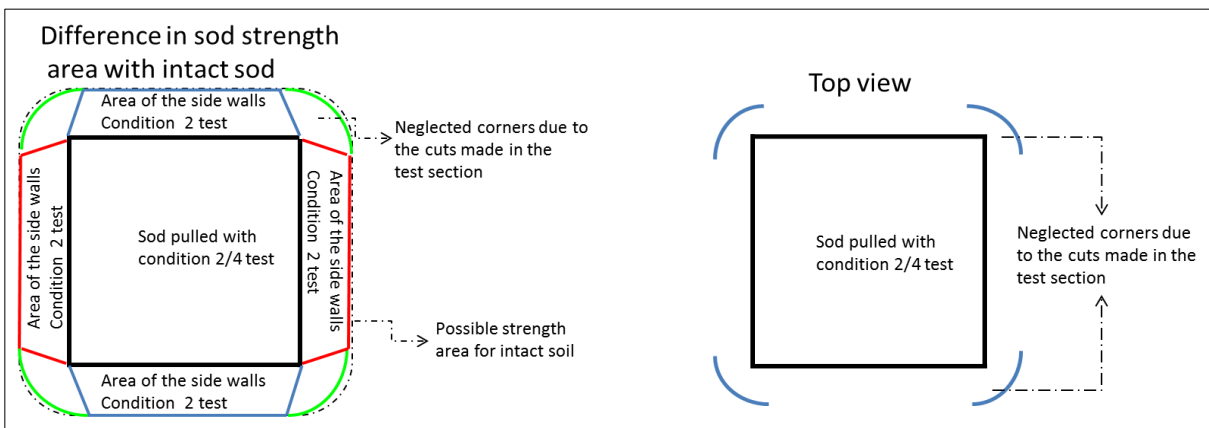
Figure 19 - Difference in sod area between condition 2 and 4 test

Figure 20 - Photos of the side and bottom view of missing corners due to the cutting

Table 9 - Shape factor per frame size

Frame size	Factor
10x10	1,20
15x15	1,15
20x20	1,10

The factors are an estimation of the excluded area of the corners in depth, but it is difficult to say how much these corners exactly contribute to the total force of the intact sod. An estimation of the area is given and this is related to the total force resisted by the sides and bottom. It is not exactly determined how big the influence of the cutting of the corners is. It has influence on the resistance of the sod, but other factors (like the angle of internal friction) can also influence these areas. But since it is an approximation of the strength of an intact sod, a small factor is justifiable.

An estimation for the shape factor of the 10 by 10 frame is also given, but since this frame size generates inconclusive results, the data and the shape factor are not further used in this thesis.

6.2   Theoretical method of Hoffmans

Hoffmans developed another way to determine the strength of an intact grass sod. The second method to calculate this strength is based on the theoretical decrease of root intensity over the depth. It is established by Sprangers (1999) that there is an exponential decrease of the root intensity over the depth of the sod. Since the roots provide most of the strength in the sod, the decrease of roots will lead to a decrease of strength. Figure 21 shows a schematic view of the exponential decrease of strength over the depth, where z is the thickness of the sod, λ_{ref} the reference height where the grass cover becomes unstable, $\sigma_{grass,\,c(0)}$ the tensile stress at ground level and $\sigma_{grass,\,c}$ the tensile stress at any given level. The black line represents the theoretical exponential decrease of roots over the depth, where the blue line represents one side. The grey area is total strength of the side up until depth z.
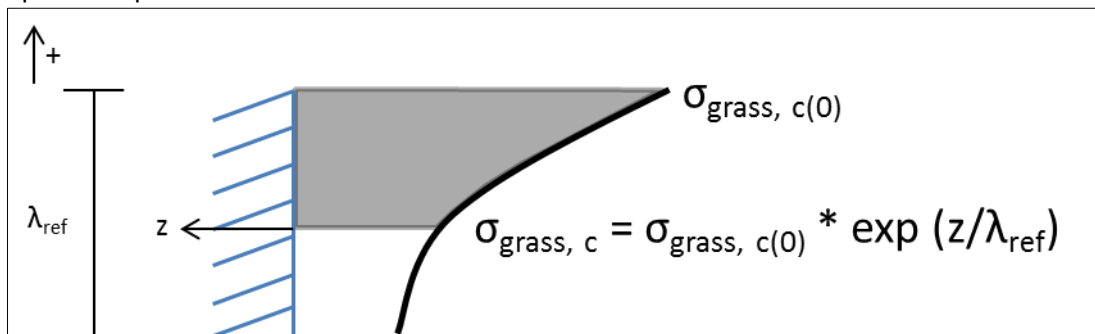
Figure 21 - Schematic view of exponential decrease of root density over the depth

The reference height is based on the tangent of the exponential function root intensity. This is set constant at 10 centimetres for grass in the Netherlands. Gijs Hoffmans developed Equation 4 on the basis of this figure, see also Appendix D. Two relations can be established, which can give an approximation of the strength of an intact sod, calculated from the condition 2 or 4 test. He assumed an average thickness of the sod of 5 centimetres. When applying this to the equation in the figure, it leads to a factor of 0.6 for the strength of the roots at 5 centimetres depth compared to ground level. This is the basis for the condition 4 test, where only the bottom roots at 5 cm depth have influence on the strength.

For the condition 2 test the same rules apply, so the factor 0.6 for the bottom strength is correct. A factor for the 2 sides has to be a found, which is done by taking the integral over the depth up to point z, giving the theoretical tensile stress of one side.

$$\frac{1}{z} * \int_{-z}^{0} \sigma_{grass,c} * e^{\left(\frac{z}{\lambda_{ref}}\right)} * \mathrm{d}z = 0.787 \approx 0.8 \qquad (4)$$

This derivation leads to the following two equations for the calculation of the strength of an intact sod. Equation 5 is for the condition 2 test and Equation 6 for the condition 4 tests.

$$\sigma_{grass,c2} = \frac{F_2}{0.6 * A_b + 2 * 0.8 * A_s} \tag{5}$$

$$\sigma_{grass,c4} = \frac{F_4}{0.6 * A_b} \tag{6}$$

Where F_2 is the measured maximum force for the condition 2 test and F_4 the maximum measured force for condition 4 test. However, during the tests performed in Millingen aan de Rijn and Boonweg the average thickness of the grass sod was around 7 cm (see Appendix C1). With the same reference height the factors change slightly, leading to the Equations 7 and 8 for condition 2 and 4 respectively.

$$\sigma_{grass,c2} = \frac{F_2}{0.5 * A_b + 2 * 0.7 * A_s} \tag{7}$$

$$\sigma_{grass,c4} = \frac{F_4}{0.5 * A_b} \tag{8}$$

In Figure 22 all the regular tests are plotted per location with these last two equations. On the vertical axis is the calculated critical mean grass normal stress plotted. There are four different kind of test expressed as a critical mean normal stress for every location. These are the condition 2 and 4 tests for the 15x15 and 20x20 frame size. On the horizontal axis is each location plotted twice, where the first half is for the condition 2 tests and the second half for the condition 4 test. The left data points per location represent the data from the 15x15 frame and the right data points the 20x20 frame size.

The data points of the 10x10 frame size are (again) not plotted in the figure. The influence of the cutting of the sides is so large that it gives conflicting and inconclusive results.
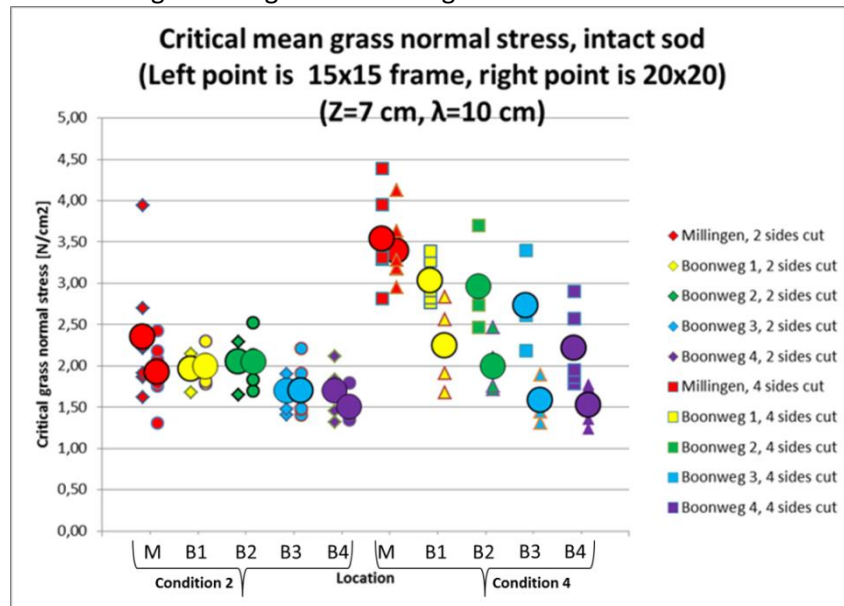
Figure 22 - Calculated critical stress for an intact sod with the theoretical method (results shown per location)

Conclusion and discussion
The above figure shows that the condition 2 results are quite similar for both the 15x15 and 20x20 testing frame. The values for the condition 4 tests are definitely not constant. The 20x20 frame is close to the values of the condition 2 tests, but the calculated stresses for the 15x15 frame are much higher. This should not be the case; the calculated total tensile stress should be the same for all test methods. Both test methods use the same type of grass, therefore a small difference can possibly exist, but not of this magnitude.

Increasing the reference height, causes the values of the 15x15 frame size and condition 4 test to come closer to the other values. The bigger the reference height is, the smaller the difference in outcome. But since the reference height is established on the basis of an exponential decrease of the roots over the depth, this can only be changed when a different relation is assumed. It is theoretical possible to increase the reference height up to the end of the root layer, which is approximately at 20 cm depth. But even then there is a calculated factor of 1.33 difference which is hard to explain. Further research should be conducted in order to determine if this discrepancy also appears at other locations.

The reference height is assumed as a value which is constant in the Netherlands. It is likely to assume that this value is also depends on the type and maintenance of the grass sod. Another type of grass or maintenance gives a different root system, therefore also a varying decrease of the roots over depth. This influences the reference height, which should be studied in more detail in another study. However, in this research the reference height will be considered as a constant of 10 cm.

6.3   Comparison of both methods

There are two methods given for calculating the strength of an intact grass sod from the sod pulling tests. In this section both methods will be compared in order to check whether the theoretical method from Hoffmans gives the same results as the more practical method developed in this thesis. When this is the case, a relation is found between the imposed tensile force on the grass sod and the available theory. All the data points per test method are averaged in one value per location. Each dot and rectangle in Figure 23 is the average of the calculated tensile stress per method. The larger dots are the average over all the tests from that method. The left points of the same colour are from the theoretical method from Hoffmans. The right point is calculated with the practical method developed in this thesis.
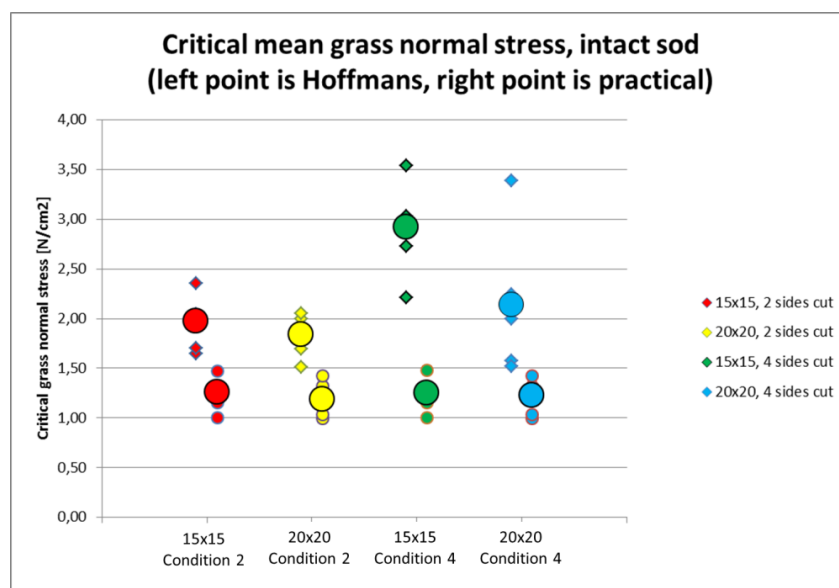
Figure 23 - Comparison of the theoretical and practical methods for calculating strength of intact sod

Conclusions
The graph shows that both methods give different results in tensile stress. For the new practical method, the values are in the same range for both methods of testing (2 or 4 sides cut). For the theoretical method, the values are higher and more scattered. Also there is a big unexplainable difference for the 4 sides cut loose.
It is possible to get both methods in the same order of magnitude when implementing an empirical coefficient. This might be defended by the fact that the theoretical equation is for example not influenced by the weather (temperature, precipitation) and the composition of the grass (amount of herbs, coverage). These factors influence the results found in the field tests. These vary not only per

location, but also per day. When this coefficient is 1.6 the theoretical results are more in line with the practical approach, except for the 15x15 frame size and 4 sides cut. However, this factor is too large to be contributed solely to the different influences, so one of the methods is not a close representation of reality.

Discussion
The difference in the 15x15 frame size with 4 sides cut and that of 20x20 frame size in the theoretical approach should not exist. This difference is also visible in the comparison between both methods (including the coefficient). Since the tests are performed at the same locations and the area of the different frame sizes is compensated for, there should not be any difference. No explanation can be given at this time why this difference appears. Further research has to be done in order to tackle this problem.

The question is whether the theoretical approach overestimates the tensile stress of the grass sod or the practical equation underestimates this stress. The theoretical approach uses an ideal situation, where the weather has no influence. Furthermore the influence of herbs is not really considered since the number of roots does not make a distinction between grass and herb roots. Both have a different strength and give therefore different results in the end. Also local coverage and maintenance are not applied in the theoretical results. The reference height is taken constant for all the grass layers in the Netherlands, but this might not be the case. When the reference height is increased, the calculated tensile stresses are decreased. When the reference height is set at 50 cm (not a realistic value) both methods are also in the same order, except again for the condition 4 test with the 15x15 frame size.
It is also possible that the practical equation underestimates the strength of an intact grass sod. This can be partly true, because the cutting of the sides does influence the measured results. However, the empirical coefficient should be added to the shape factor, which will result in a shape factor (α in Equation 2) between 1.76 and 1.92. These new shape factors are too high to be contributed for the cutting of the corners. The results from the practical method are less influenced by the weather, local coverage and maintenance. Therefore, it is more likely that the theoretical approach overestimates the strength of grass, so an empirical coefficient should be used on this equation in order to give similar results as the practical approach. In the following parts of this thesis the practical method and its values will be used for further research, since it provides more accurate results for all testing methods.

6.4   Factor intact sod
Now there is a method established for calculating the strength of an intact grass sod, it is interesting to see if there is a relation between this calculated strength and the measured strength from the condition 2 or 4 tests for different frame sizes. If there is a relation between the condition 2 or 4 test with the strength of an intact sod, it can half the total number of tests. Since the practical method is expected to be more accurate, this method is applied from here on in this thesis.

In Appendix C2 the relation for the measured strength of the different frame sizes was studied. While there was no real recurring factor between the forces for the 15x15 and 20x20 frame size, it did not result in an empirical factor. The same was concluded for the relation between the condition 2 and condition 4 test for the same frame sizes, see Appendix C3.

Figure 24a shows the amplification factor (on the vertical axis) with which one could calculate the force needed to lift an intact grass sod from the condition 2 test. For every location and every frame size (on the horizontal axis) the factor has been determined. The factors are calculated from the force of an intact grass sod divided by the corresponding force of the condition 2 test. The same applies to Figure 24b, but here the relation between the force of the condition 4 test and the strength of an intact grass sod is plotted.
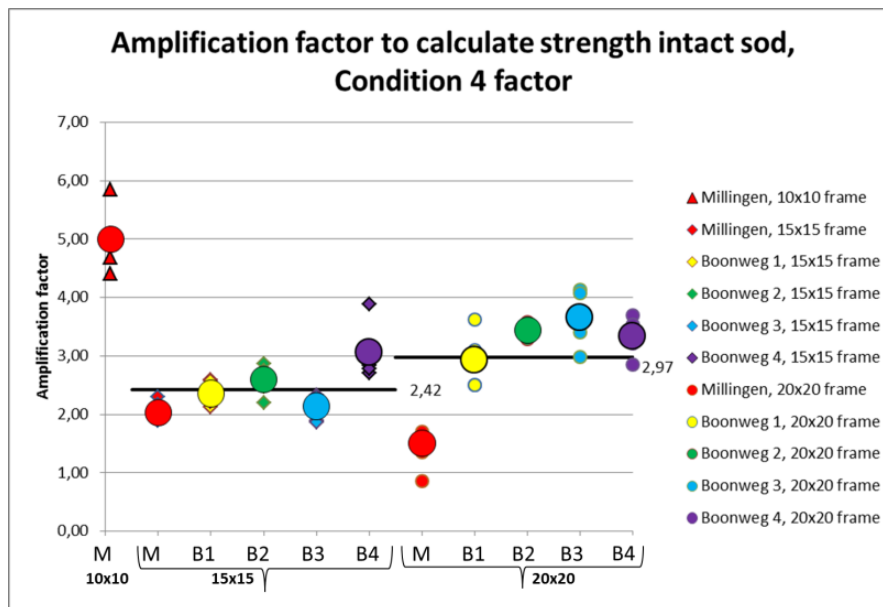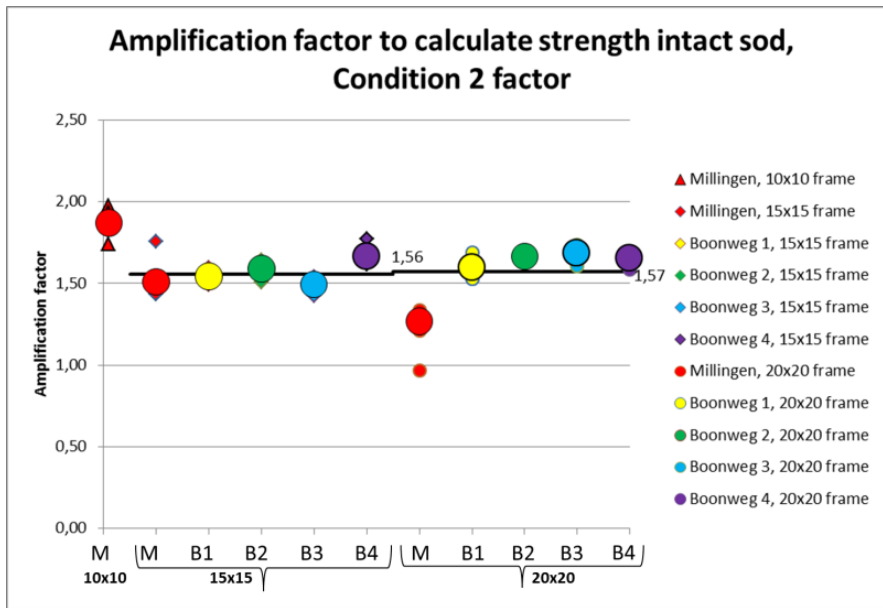
Figure 24 a,b - Amplification factor for the calculation of the strength of an intact grass sod from the condition 2 and 4 test

When looking at the amplification factor for force needed to pull out an intact sod, the values are expected to be higher than one. If the factor is smaller, which is the case in Millingen for one test, the strength of an intact sod is smaller than that of 2 or 4 sides cut loose. This should not be possible, but this is a result of the coupling of the data. The value for that condition 2 test was so small that there was no corresponding value with the condition 4 test found during testing. Since the averages are the most important values here, this point can be neglected.

Different locations have a different type of maintenance, which result in different kind of strengths. But in this case the amplification factor is not influenced by this, since it is about the relation between the measured strength and the corresponding values for an intact sod. Both originate from the same grass sod. Therefore the differences per location cancel each other out in the factor. So expected is that the factors of different locations are in the same order, where small differences can be possible. These differences appear because of different root structure in the horizontal and vertical plane.

All these factors can also be estimated from a theoretical point of view. This can be done by looking at the total area of both the tested sod and the theoretical area of the calculated intact sod. When assumed that a given area corresponds linear to the measured force, the difference in area is in the same order as the factors calculated above. The assumption is valid since a larger area has more roots inside the sod which leads to a higher strength of the sod. However, this does not account for differences in horizontal and vertical planes in the sod, which have different root structures. When the estimation is made for the different areas of corresponding frame sizes, the factors from Table 10 are expected.

Table 10 - Theoretical estimations of the amplification factor

Frame size	Sides cut	Theoretical
10x10	2	1,80
	4	3,60
15x15	2	1,70
	4	3,30
20x20	2	1,55
	4	2,64

Conclusions

Table 11 compares the theoretical values with the calculated (practical) values from the tests.

Table 11 - Comparison of theoretical and practical amplification factors

		Strength		
Frame size	Sides cut	Theoretical	Practical	Deviation
10x10	2	1,80	1,87	4%
	4	3,60	5,00	39%
15x15	2	1,70	1,56	-9%
	4	3,30	2,42	-27%
20x20	2	1,55	1,57	1%
	4	2,64	2,97	13%

When looking at the practical strength factors, there is a constant factor for calculating the force of an intact sod from the value of the condition 2 tests. There is not much scatter in the data for the 15x15 and 20x20 frame sizes. A factor of 1.56 can be used for both frame sizes in order to calculate the strength of an intact sod. This factor lies close to the theoretical factor estimated by the areas. Since this seems like a clear relation the number of tests can be halved for determining the strength of a dike section and only condition 2 tests have to be performed.

For the 10x10 frame size the 2 factor is around 1.9 for the practical application. Theoretically this was estimated around 1.80 so also here the relation looks applicable. This is only shown for the agreement between the practical and theoretical values, since the 10x10 frame size is not preferred for testing.

The condition 4 factor is not as constant as the condition 2 factor. The results are more scattered in the same location and between the different locations. This results in an unclear relation between the condition 4 test and the strength of the intact sod. This becomes also apparent when comparing the average practical factors and the theoretical estimated factors. There is a bigger difference between these values, especially for the smaller frame sizes. Therefore the condition 4 factor should not be applied for estimating the strength of an intact grass sod.

So for future testing, only condition 2 tests have to be performed, since the strength of an intact grass sod can be calculated from that by multiplying the measured strength with 1.56. For determining the critical grass mean normal stress, the calculated value for the force has to be divided by the area. Another benefit from this is that the condition 4 test is more influenced by the cutting of all the sides, therefore the measurements are more reliable, when only testing condition 2 for different frame sizes.

Discussion

What is notable from the previous section is that the condition 4 factor is not in line with the assumption of the linear relation between the area and the corresponding strength. This can be explained by the fact that the most roots are in the top 5 cm of the sod. Since the bottom shear plane is around 7 cm deep, there are fewer roots present at that level. This means (on average) that there is less resistance against the uplifting force at this level. Looking at the sides, it starts at ground level up until 7 cm depth. Almost all the horizontal roots are present in this area. However, the sides do not contribute to the strength of the sod for the condition 4 test. So the measured strength per area of the condition 4 test results in an underestimation for the strength of an intact sod. This means that the theoretical estimation is not fully correct because of assumptions made in this thesis. This can also explain why there is a small difference between the theoretical and practical factor for the condition 2 test. However, since here 2 sides already contribute to the strength, the average strength per area is higher than with the condition 4 tests. As a result there is a difference present, but it is not that large. Because of this it is beneficial to use the practical condition 2 factors to determine the strength or stress of an intact sod instead of the theoretical amplification factor.

7 Grass sod properties

In Chapter 5 the parameters which influence the strength of the grass sod have been determined, while in the previous chapter the strength of an intact grass sod is calculated. In this chapter the focus will be on the properties of the grass sod. First the displacement where the maximum measured force occurred will be discussed. It is important to determine this displacement because it will provide insight in the behaviour of the grass sod under wave overtopping conditions. In Section 7.2 the influence of the clay layer underneath the grass sod will be explained. When erosion starts on the slope, a part of the grass will wash away. The remaining clay layer will still have roots in its structure, but it is not known how erosion resistant this remaining clay layer is. The influence of the bricks underneath the sod on the strength of the grass is explained in Paragraph 7.3. These bricks hinder the growth of the roots in vertical direction so it is interesting to see this influences the measured strength. After that the fatigue of a grass sod will be discussed. The modulus of elasticity is a good indicator for the fatigue of different materials, so this will be handled at the end of this chapter.

7.1 Displacement at point of maximum resistance

It is interesting to investigate the displacement at which the maximum resistance in measured. This can be done from the force and displacement meter provided by Deltares during the tests. It will provide insight into the behaviour of a grass sod. There might be a constant displacement where the force is at its maximum when lifting the sod up. If this is the case, it can be determined how far the sod has to be lifted in order to find the maximum force.

The starting point of the measurements for all the tests set at a constant displacement. This value is set to zero, so that the other points can be calculated from here. When the maximum forces per test have been determined, the corresponding displacement can be found in the data. This is done for all the regular tests with the 15x15 and 20x20 frame sizes. Those displacements are plotted on the vertical axis in Figure 25. The figure is split into two sections, one for the condition 2 tests and one for the condition 4 tests. Both frame sizes plotted next to each other per location where the left coloured point is for the 15x15 frame and the right for the 20x20 frame size.
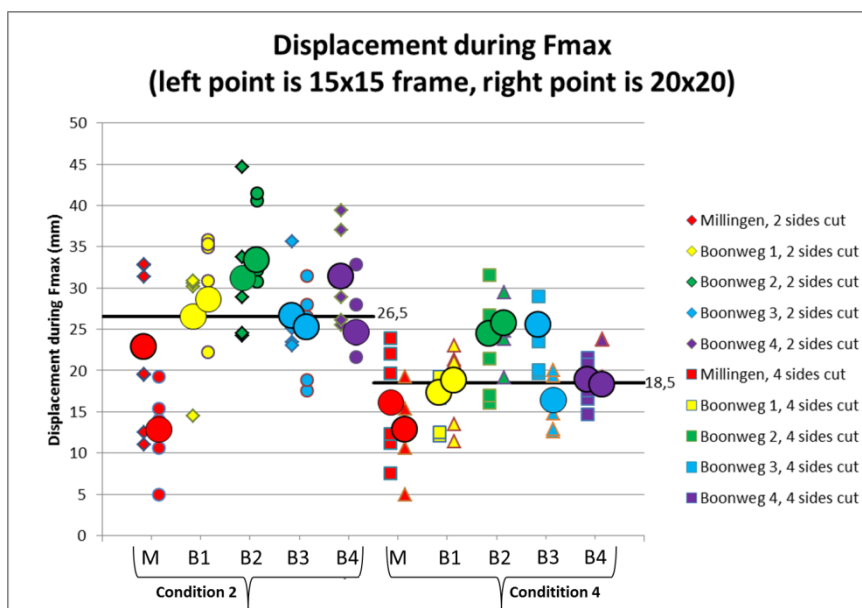
Figure 25 - The measured displacement at the point of maximum resistance

The figure shows a lot of scatter of data points around the averages. There is however a clear distinction between the values for the condition 2 and 4 tests. Furthermore the frame size does not really influence the displacement at which the maximum force occurs. The averages of the displacement per location are mostly in the same order.

The number of sides loose does influence this value. It can be seen that when only the vertical bottom roots are still intact the maximum measured force is averaged around 18.5 millimetres. When only 2 sides are cut, this maximum occurs around 26 millimetres. However, the scatter around the averages is about 30% of the value. When the different locations are taken separately, the average values still fluctuate, but more important is that the scatter decreases to about 20%. One explanation for this can be that the type of maintenance has influence on the vertical and horizontal build-up of the root system. This is in line with earlier test results and theory.

Since there is a clear difference in displacement between the condition 2 and 4 tests, the grass sod behaviour can be further examined. When only the bottom roots are attached to the surrounding sod, there is a displacement possible of approximately 18 mm before the grass sod loses most of its strength. When the bottom roots and the roots through the two remaining sides provide resistance against the displacement, the maximum force occurs around 26 mm. So there is a clear influence of the 2 sides on the displacement. The 2 sides do not only contribute to the measured strength of the sod, but also to the maximum displacement. In order to visualize the influence of the sides, the force displacement Figure 26 is constructed. This figure shows the progress of the force against the displacement, which provides insight into how the bottom and the sides interact and give strength to the sod.

In order to draw this figure with the approximated strength of the sides, two tested sections were chosen which are representative for most of the data points (and a good fit with each other). The approximated strength of 2 sides (blue line) is calculated by subtracting the strength of a condition 4 test (yellow line) from the condition 2 test (red line). When the strength of the 2 sides is added to the condition 2 test, it gives the strength of an intact sod (black line). The strengths of these tests are taken at points of similar displacement. This leads to an approximation of how a sod behaves under a vertical elevation. This approximation is valid since grass has a constant modulus of elasticity (see Chapter 7.5). Because of this, it has the same mechanical properties and is it possible to subtract forces from one another.
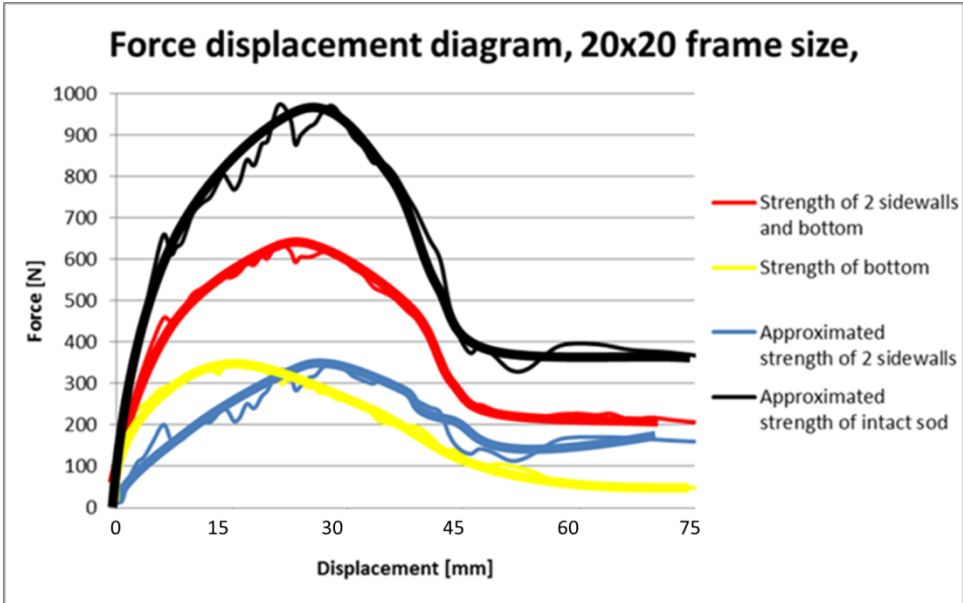
Figure 26 - Displacement at which the maximum resistance is found for different testing conditions

This figure is a visualization of the behaviour of grass under vertical displacement. From that can be concluded that the maximum force with 2 sides intact occurs at a moment where the bottom roots do not generate the biggest resistance against the uplifting force. It is a combination of the bottom roots and the strength of the sides that results in the largest resistance. The maximum resistance of the intact sod is established from the practical approach, where the displacement under maximum resistance is around 30 mm. So due to the sides, the sod can withstand larger displacements before the maximum is reached. This is also seen in wave overtopping simulator tests at the Boonweg 3 and 4, where a bulging mechanism was spotted, see Figure 27. This resulted in a volume of water under the grass sod, lifting the grass sod upwards for an area of 1 m^2. The water leaked away after the wave had passed, but after a couple of times the whole area broke free and washed away, see also the report of Infram 2008.

Figure 27 - Bulging of the grass sod during wave overtopping simulations (Infram 2008)

7.2 Influence bare clay

The structure of the dike is generally the same. The top layer consists of a grass sod built on a clay layer of minimal 70 centimetres thick. During wave overtopping small areas of grass can erode away, but the underlying clay layer still provides some resistance against the overtopping waves. This clay layer protects the core of the dike. When it is eroded, the dike core will be exposed and the dike section will soon fail. So it is important to check how strong the remaining clay layer is. These tests are performed at Boonweg 1, where the top layer is removed from a dike section till 6 cm depth and later till 10 cm depth. There are still roots present at these depths, which provide extra resistance against the erosion.

In May 2008 the quality of the clay at Boonweg 1 was determined (Infram, 2008). The average thickness of the clay layer was 60 cm, with underneath a core of sand. The erosion resistance of the clay was comparable with category C3 clay. The Atterberg limits were very low, the small particle content was low and the sand content was high. The porosity of the clay was about 45% overall. The peak strength of the clay is reached after a small strain percentage with an average value of 2.4 kPa and an average angle of internal friction of 30.7°. The infiltration tests showed that the shear strength decreases considerably after saturation of 1 or more hours. The permeability of the clay is about 2x10-5 m/s which is quite a low value. It is assumed that the quality and the parameters of the clay layer have not changed in the past years.

The tests on bare clay are performed at Boonweg 1 as a condition 2 test for the 15x15 frame size. In Figure 28 the measured values of the 4 bare clay tests are plotted for their measured maximum force. Also the regular tests are plotted in the figure in order to see the difference. It was noted that during the clay tests the plane of shear was on the depth of the pins (see Figure 29 a,b). No extra thickness is pulled up, because there are not enough roots to keep the clay aggregates together.
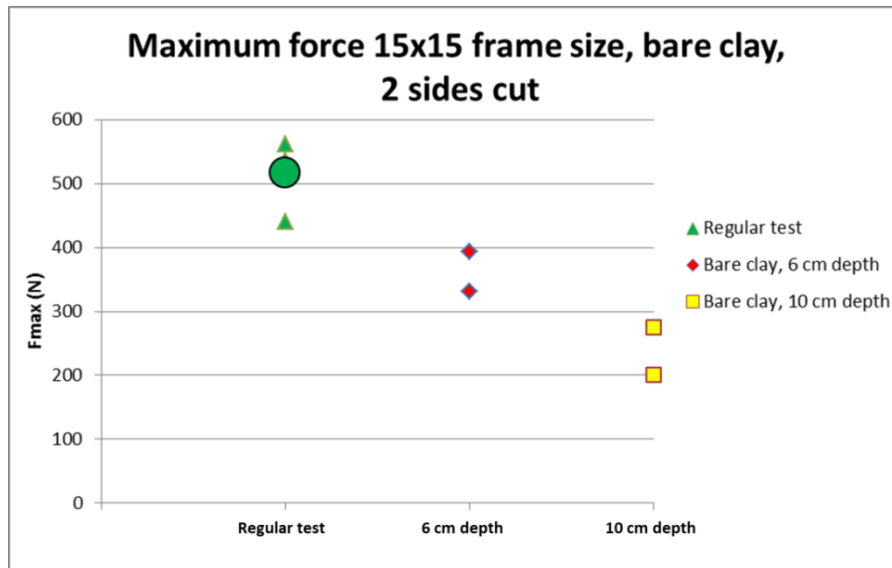
Figure 28 - Measured maximum forces of regular and bare clay tests at different depths

At a depth of 6 to 10 centimetres, there are not that many horizontal roots present for extra support for the clay. The deeper roots do not branch out to the sides as much as the roots on ground level. So there are only some vertical roots present at these depths, which provide support against the uplifting force. In Figure 29a it can be seen that there are still quite some roots present at the test at 6 cm depth, where the bottom of this sod is at approximately 10 cm depth. These roots provide extra resistance against the uplifting force, but since the most roots are in the top 5 cm, the strength of the bare clay is lower than that of a grass layer. The force needed to extract a clay sod at 6 cm depth is about 70% of the maximum strength needed for a normal grass sod.

Figure 29b shows the bottom of the sod of the test at 10 cm depth, where the bottom is at approximately 14 cm depth. At this depth, most roots have disappeared in the clay. Only a small percentage of the total number of roots reaches this level. The strength of the clay sod at 10 cm depth is about 45% of the original strength. This means that even a few roots have a huge impact on the strength. The clay however was not completely saturated at this depth. The infiltration time is too big for the water to reach this depth (up to 15 cm).

Figure 29 a,b - Pulled out clay sod at a depth of 6 cm (a) and 10 cm (b)

To test the bare clay, a relative large hole had to be made in the dike. Because this was not in the original test set-up, only 4 tests have been performed. Looking at Figure 28, there is a quite some difference in the measured forces at the same depth. One explanation for this is that during one of the test at 10 cm depth, the sound of breaking roots was clearly present. This noise was absent during the testing of the other test at the same depth. This means that at greater depths underneath the grass the roots are not so evenly spread out. There are fewer roots present, so the difference is greater at a local scale.

The strength of bare clay has been determined on different depths and therefore it is interesting to see what the critical mean normal stress is for bare clay. The strength is calculated by multiplying the measured maximum by the factor 1.56 (see Chapter 6.4) and then divided by the area. This results in the values shown in Figure 30. The decrease in critical mean normal stress is the same as for the strength. In previous research is was established that the strength of pure clay of decent quality was only 0.075 N/cm^2 (Hoffmans, 2012). The values determined here are significantly higher. Therefore the few roots and the structured clay have an enormous impact on the strength of the clay layer.
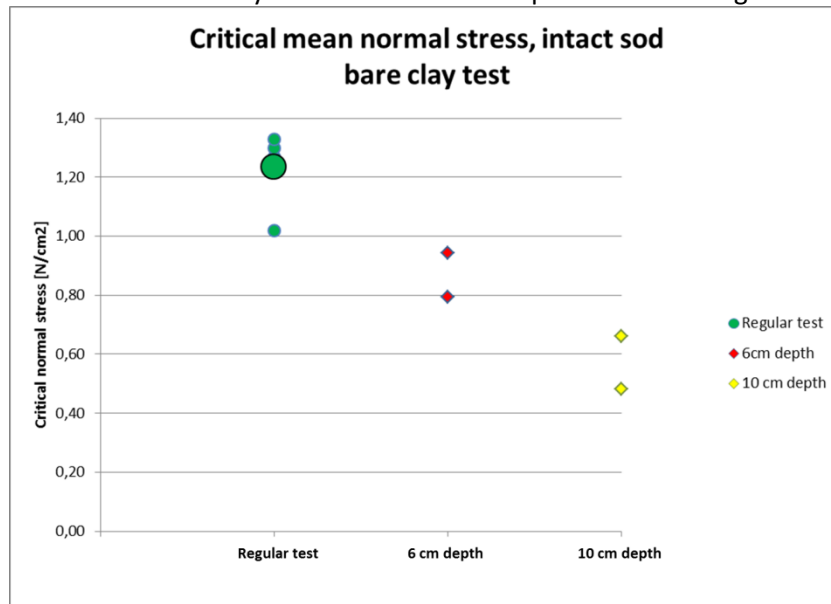
Figure 30 - Critical stress for intact sod of regular and bare clay tests at different depths

7.3   Influence of stones underneath the grass sod

At the locations of the Boonweg, there are bricks present at the toe of the dike. These bricks were part of an old path on the dike. However, during the last expansion of the dike these bricks were not removed before elevating the dike. There is a clay layer of approximately 10 centimetres depth above the bricks, which is covered by grass. It is important to check whether these bricks are beneficial for the resistance against erosion or that it weakens the toe, because the roots of the grass cannot reach the deeper clay layers. When the grass is eroded, the bricks provide almost no resistance against the overtopping wave. There are also bricks present at the fences, which separate the different sections of a dike. These bricks are placed as reinforcement of the dike near these fences. So some tests are also done here in order to check the resistance of the grass sod against erosion.

There are 4 sod pulling tests above a brick layer done at Boonweg 2 as a condition 2 test for the 15x15 frame size. Two tests are done at the toe of the dike and two tests near the fence. In Figure 31 the critical mean normal stress of the tests are plotted. The strength is calculated by multiplying the measured maximum by the factor 1.56 (see Chapter 6.4) and then divided by the area. In the figure are also the regular tests plotted, in order to see the difference in strength between them.
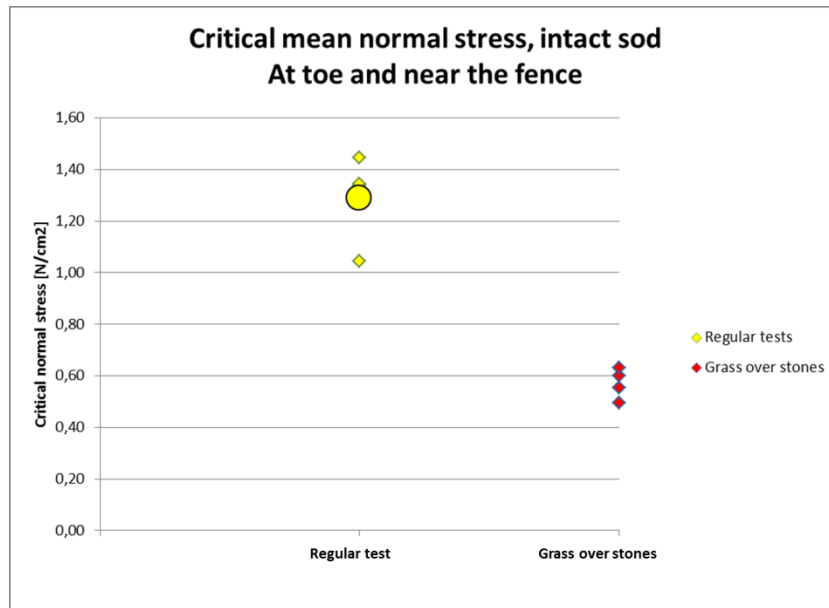
Figure 31 - The influence of bricks on the measured strength of an intact sod

The figure shows that the sections which are reinforced with bricks provide low resistance against the uplifting force. There is more than a factor 2 difference in measured strength compared to the regular tests performed on the slope. The toe and near the fence are places which are more difficult to maintain by mowing and hay-making. But that cannot explain this difference in strength. The problem with the brick layer at 10 centimetres depth is that the roots of the grass sod cannot penetrate this layer. So the root system can only develop up to this depth. This results in less and smaller roots and thus in less resistance against an uplifting force.

During the wave overtopping simulations at the Boonweg damage occurred first at the toe of the dike. After the grass layer was eroded, the bricks were soon washed away since they are not anchored into the soil. This leads to the conclusion that a brick layer should not be used underneath the sod at places where higher loads are expected. The layer will only weaken the sod further, leading to an increasing erosion rate at those locations.

7.4   Fatigue tests

During this thesis, a lot of tests are performed. The regular tests are in the form of rapid tests, where the sod is lifted in one time until it fails. However, quite some tests are also performed with repeatedly lifting the grass sod a couple of centimetres and releasing it back to its original state. In this way the fatigue of the grass sod can be tested. The fatigue tests are done with an increasing displacement of 5 mm after 10 repetitions. After every tenth repetition the displacement, with no force acting on the sod, has been measured. This makes it possible to see how the grass sod behaves under varying displacements. The fatigue tests are mostly performed with 4 sides cut loose, but additional tests are performed with 2 sides still intact.

There are 2 different types of measurement available: the readings of the tension gauge and the data gathered by the Deltares equipment. The maximum force for every repetition (10 times per induced displacement) is measured in Newton and shown in Table 12. In this table the measured forces are given in different colours, where a higher force corresponds to a green colour. The lower forces are shown in red. This is also visible in Figure 32. This way, it is easier to see the difference per repetition in the force needed to pull out a sod after a certain displacement is reached. There is a row with the term "moved [in mm]" in the table. The values in this row are the measured displacement when there is no force acting on the sod, after the ten repetitions for the same displacement. With these values it might be possible to look at the elastic and plastic behaviour of the grass sod.

Also force displacement graphs can be made from the data, for example Figure 33a where the graph is constructed from the Deltares measurements and the Figure 33b from the tension gauger. There are only 4 tests shown: 2 condition 4 and 2 condition 2 tests for the 15 by 15 frame size. There are in total 26 fatigue tests performed, but the following figures are chosen to be representative for all the data. However all the fatigue tests have been used for the analyses and conclusions.

Table 12 - Fatigue tests for 15 by 15 frame size and condition 4 test showing the maximum force for every repetition

Section / test	Displacement	5	10	15	20	25	30	35	40	45	Extraction Force
Section 6, 15x15 frame size; 4 sides cut	1	140	230	260	300	320	320	290	240	180	110
	2	140	100	200	250	270	220	220	190	110	
	3	90	140	190	230	210	230	220	160	90	
	4	100	120	180	250	220	210	220	170	100	
	5	70	110	160	210	210	210	210	170	90	
	6	100	110	170	210	210	180	190	140	90	
	7	120	90	190	210	210	200	190	130	90	
	8	110	110	180	190	200	170	190	130	80	
	9	80	120	180	200	190	180	180	130	70	
	10	120	110	200	170	220	190	180	130	90	
Moved [mm]	3	8	9	13	18	24	27	33	39		
Section 7, 15x15 frame size; 4 sides cut	1	120	180	220	280	320	320	320	260	180	130
	2	120	180	220	240	270	260	280	200	140	
	3	120	160	220	210	250	270	230	180	130	
	4	110	210	180	230	270	230	240	180	90	
	5	100	210	180	210	230	230	240	190	100	
	6	100	100	180	190	220	210	240	160	100	
	7	100	110	180	220	230	190	190	180	100	
	8	110	60	180	190	220	220	210	130	110	
	9	100	120	160	180	230	210	200	130	90	
	10	100	130	160	200	230	240	230	150	100	
Moved [mm]	4	7	12	16	19	25	30	36	40		

Figure 32 - Colour scales for the measured forces during fatigue tests
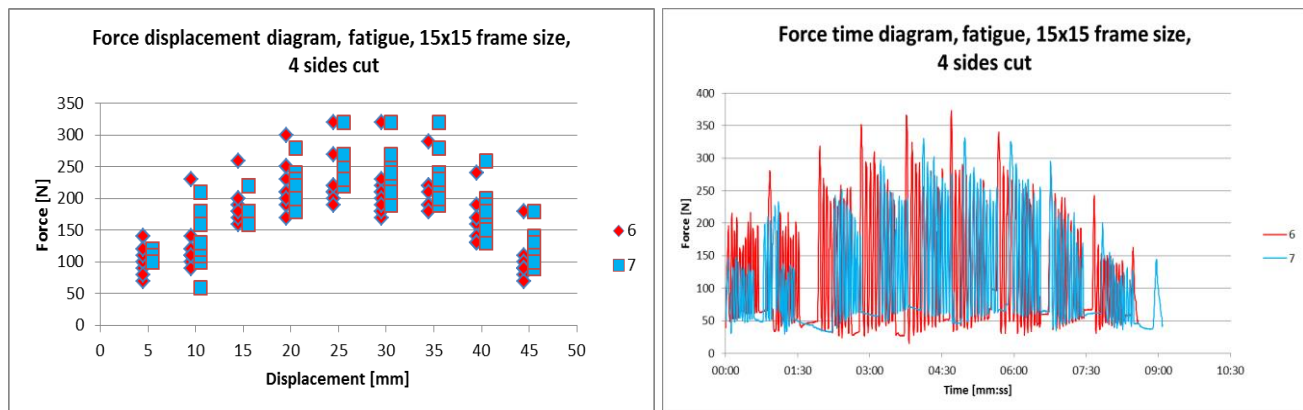

Figure 33 a,b - Force displacement graph for fatigue tests with 15 by 15 frame size and condition 4 test

The condition 2 fatigue tests are shown in Table 13 and Figure 34 a,b.

Table 13 - Fatigue tests for 15 by 15 frame size and condition 2 test showing the maximum force for every repetition

Section / test	Displacement	5	10	15	20	25	30	35	40	45	50	55	60	65	70	80	Extraction Force
Section V1, 15x15 frame size; 2 sides cut	1	80	150	180	180	200	210	190	210	220	220	230	220	210			
	2	110	120	140	130	150	170	160	160	160	200	210	150	140			
	3	80	100	120	150	120	130	130	120	180	150	180	130	90			
	4	80	100	110	160	120	140	140	160	180	160	150	160	100			
	5	70	80	130	140	110	160	130	140	190	140	110	110	110			
	6	60	70	90	130	120	150	130	170	140	120	170	120	80			150
	7	70	90	120	140	130	110	140	130	150	120	140	110	80			
	8	80	60	130	100	110	130	140	110	140	120	160	120	70			
	9	70	80	110	110	120	120	130	130	140	140	140	120	90			
	10	80	90	110	110	130	130	140	160	180	130	170	120	70			
	Moved [mm]	2	4	7	10	12	14	15	20	25	27	31	36	38			
Section V2, 15x15 frame size; 2 sides cut	1	140	210	230	240	240	240	270	220	230	240	230	190	210	180	130	
	2	140	160	160	200	210	210	180	180	200	210	210	180	160	160	110	
	3	110	160	160	190	170	160	160	150	180	200	160	130	140	140	80	
	4	120	140	190	170	140	180	160	140	140	180	160	120	110	140	70	
	5	80	130	160	120	140	170	130	160	180	160	170	140	140	130	70	
	6	110	160	150	130	110	160	120	180	140	150	140	140	140	120	90	130
	7	110	140	180	110	150	130	150	180	120	150	170	140	140	100	80	
	8	90	130	160	120	180	170	160	160	150	110	150	130	130	100	80	
	9	120	130	140	120	130	150	140	150	160	160	140	150	140	100	70	
	10	120	150	140	140	140	170	160	170	180	150	160	150	140	90	80	
	Moved [mm]	3	5	6	9	11	14	19	23	26	28	31	36	43	46	50	
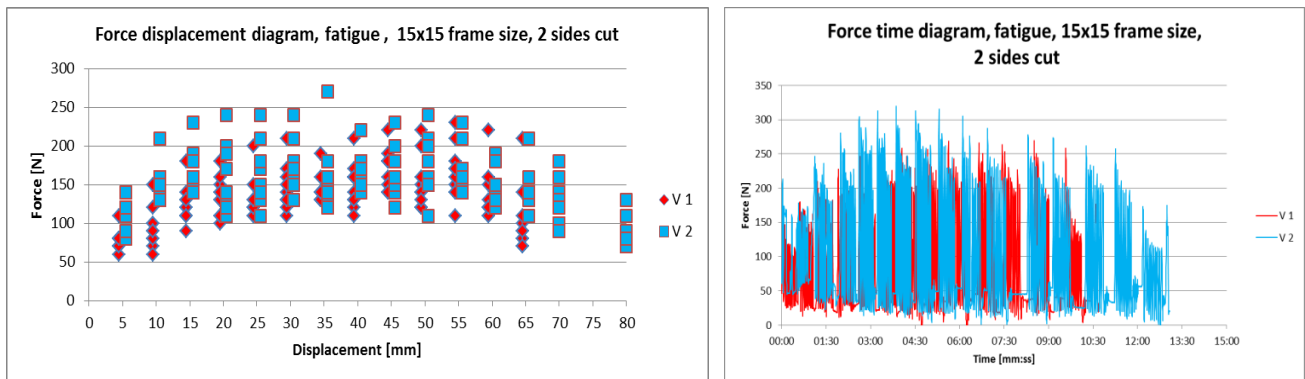
Figure 34 a,b - Force displacement graph for fatigue tests with 15 by 15 frame size and condition 2 test

During the tests the sod is pulled up for a certain displacement and then released back to its original position. However, it is difficult to pull up the sod to exactly the same imposed elevation during the 10 repetitions. It is tried with a ruler mounted on the hydraulic cylinder as reference for the elevation. Because this is not the most accurate manner, it can happen that the imposed displacement varies during the 10 repetitions with a few millimetres. This results in a deviation in the measured force.

Several conclusions can be gathered from the tables and the figures.

1. When the displacement is increased, the first pull needs a higher force to reach the desired elevation than the remaining repetitions with the same imposed displacement. For the remaining 9 repetitions the force needed to reach the given elevation decreases to an almost constant level. Most of this decrease in force is until the 4th repetition, after that it levels out. This can best be seen in Figure 33b and 34b, where the first peak in a cluster is the highest, after which it levels out.

2. There is a difference in the fatigue tests with 2 or 4 sides cut loose. This does not only relate to the measured strength, but also the maximum displacements. With 4 sides loose, only the vertical roots provide resistance against the imposed forces. After an elevation of 30-50 mm (average of 37,5 mm) all the roots are broken or pulled out, so the root system of the grass sod is completely destroyed. With 2 sides intact, the imposed elevation can go up to 65-100 mm before the grass sod completely failed. During the condition 2 fatigue tests one could look underneath the grass sod at higher elevations. This means that the bottom roots had failed, but the sides still had some resistance against the displacement. This is in line with the assumed displacement theory from Section 7.1 and can also explain the bulging mechanism (see Figure 27).

3. The maximum force with the tests of 4 sides cut loose occurs somewhere between 15 and 30 mm displacement, but on average it is at 20 mm. This is in the same order as the displacement during maximum resistance with the rapid tests (Section 7.1).
4. During tests with 2 sides intact the displacement at which the maximum force occurs is not that clear. Here the maximum lies in the range from 20 to 55 mm elevation, with an average of 35 mm. This is a bit larger compared to the rapid tests, but still higher than the condition 4 tests.
5. When looking at the displacement with no external force on the grass sod, it becomes clear that after 10 repetitions of a certain displacement the sod does not return to its original position. Because some roots are broken during these repetitions, there is a smaller tensile force which pulls the sod down. Also the own weight of the sod is not enough to push it back in original position. Because of this, there is no clear elastic or plastic behaviour of a grass sod. It is clear that during the condition 2 tests the grass sod shows more elastic behaviour, due to the horizontal roots, which fail with a larger displacement then the vertical roots.

7.5 Modulus of elasticity

All the tests discussed up to section 7.3 are rapid tests, but during wave overtopping there will be numerous uplifting forces before the sod fails. This can be simulated with the fatigue tests, see the previous paragraph. However, there is another way to provide insight into the strength of a grass sod under multiple repeating loads. If a grass sod can be compared to another (better known) wood like product, the fatigue behaviour of that material could be used for grass. In order to compare different materials, the modulus of elasticity (or Young's Modulus) should be the same. This modulus is a measure for the stiffness of an elastic material and is defined as the ratio between the stress and the deformation over the initial length. In previous research a link is made with the modulus of elasticity of pinewood, which has an E-modulus around 9 GPa. If the E-modulus of the grass sod is in the same order, the materials are comparable in behaviour. If not, another material has to be found for comparison.

The modulus of elasticity has been determined in two different ways in this thesis. For the first method values from the force displacement graphs (see Appendix B2 for examples) are taken. The point of maximum force is taken, with a corresponding displacement and a straight line through the origin is assumed. The values of the force and displacement at this point will be used as input in Equation 9. As value for the thickness of the sod, the average thickness of 70 millimetres is used as established in this thesis. The Root Area Ration is the total area of the roots in 1 square meter of the sod. This has a value of 0.0008 for good quality grass (Hoffmans, 2010).

$$E = \frac{Fmax * L_0}{RAR * A_0 * \Delta l}$$
(9)

Where:
- E = Modulus of Elasticity [N/mm^2]
- Fmax = Maximum Force [N]
- L$_0$ = Thickness of the grass sod = 70 mm
- RAR = Root Area Ratio = 0.0008 (0.8‰) for good quality grass
- A$_0$ = Area of the grass sod (depends on the size of the frame) [mm^2]
- Δl = Displacement of the sod [mm]

This calculation is done for every test in this research. The results are shown in Figure 35, where the modulus of elasticity is plotted per location. There is some scatter in the results, especially for Millingen aan de Rijn. Overall the results are in the range of 0.04 - 0.20 GPa with an average value of 0.09 GPa.
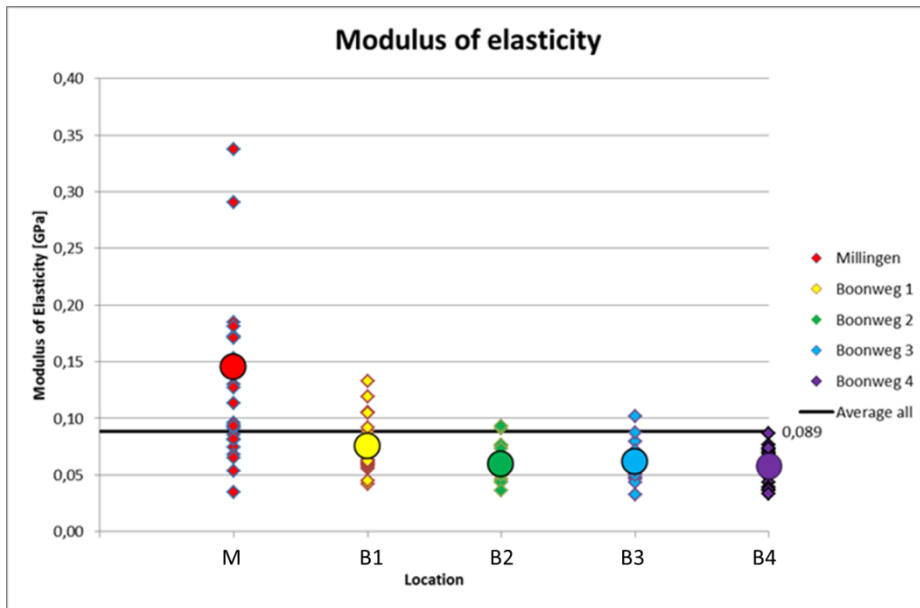
Figure 35 - Modulus of elasticity based on force displacement graph

The second method calculates the modulus of elasticity of an intact sod as a function of the tensile stress and the relative deformation. The tensile stress of the intact sod is calculated by the practical approach. The relative deformation ($\varepsilon = \Delta l / L_0$) of a grass sod is between 15 to 35% with an average of 25%. Equation 10 is used in the second method for calculating the E-modulus.

$$E = \frac{\sigma}{\varepsilon}$$
(10)

This calculation is performed again for each test in this thesis, with the results shown in Figure 36. The results are comparable to the first method, but have a slightly higher average value. Overall the results are in the same range of 0.05 - 0.17 GPa with an average value of 0.10 GPa.
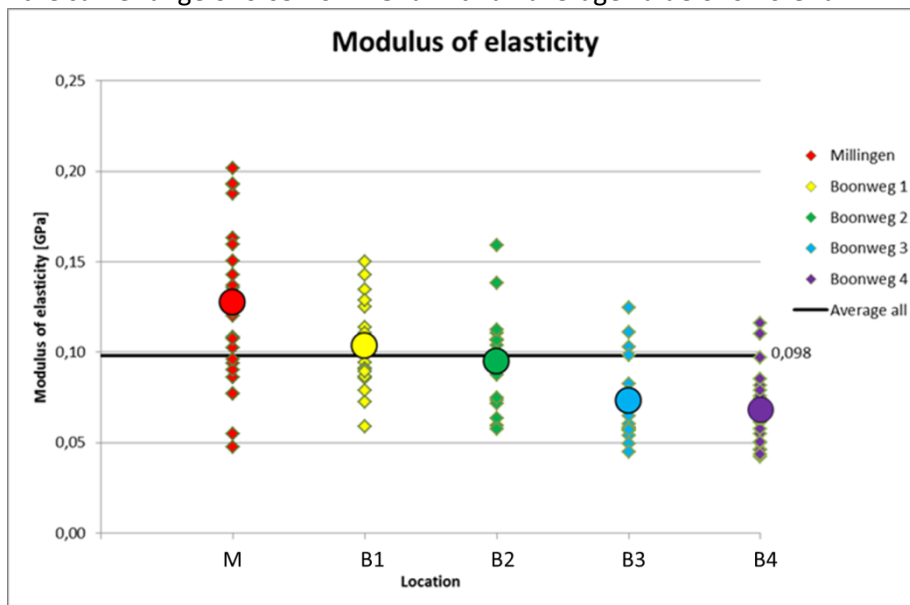
Figure 36 - Modulus of elasticity based on relative deformation

Alterra also determined the modulus of elasticity for grass, but their focus was on individual grass roots. They found an average value of 0.09 GPa with a standard deviation of about half this value. All three methods lead to approximately the same result, therefore the modulus of elasticity of a grass sod is with relative certainty 0.1 GPa. This is still a factor 100 difference with the modulus of pinewood. This is not in the same order of magnitude, therefore the two materials are not comparable in behaviour.

Since the behaviour of grass roots is not comparable with pinewood another material has to be found for comparison. This should preferably be another wood like material, because of the structure of the roots. It is hard to find an overview of the modulus of elasticity for wood like materials with such a low value. Figure 37 is made by the University of Cambridge and shows the modulus of elasticity of different materials. In this figure is grass just in the area of wood and wood products as can be seen below with the red circle. This indicates that there are some wood like materials known with the same kind of properties. The brown circle indicated the location of pinewood in this figure, which is clearly not in the same range (for wood products) as grass.
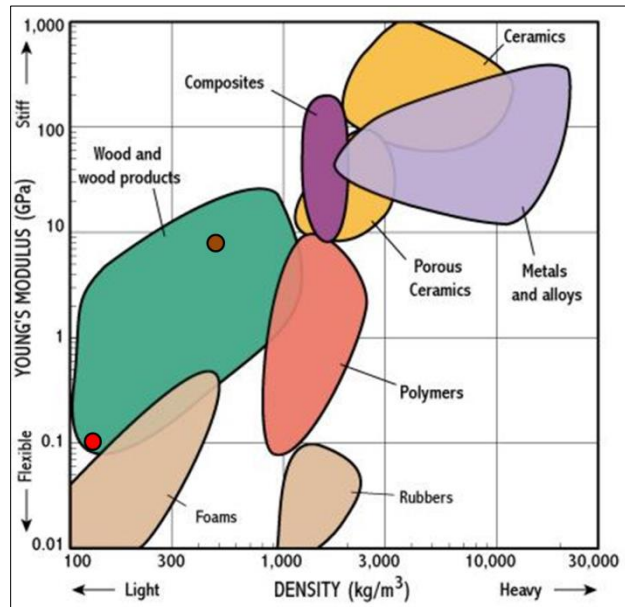
Figure 37 - Modulus of Elasticity of different materials (University of Cambridge)

It is interesting to find a wood like material with the same modulus of elasticity, since this modulus can be used as a factor for the fatigue of the material. When two materials have the same modulus of elasticity, the knowledge from both materials can be used to compare its mechanical properties. So when the properties of the comparable wood like material are better known, it can be used to provide further insight in the behaviour of a grass sod under repeating loads.

Furthermore, testing the fatigue of a grass sod is difficult and time consuming, since it has to be done as field tests. Even when the other material is not well known, it might be easier to test it in the lab. It is not possible to extract multiple grass sods from a dike with the same dimensions and root structure. If it is possible to obtain multiple cubes with the same dimensions of the comparable material, it can easily be tested in the universal testing machine.

So if this new material is found, it can provide further insight in the behaviour of the grass sod under repeating loads, which is also the case during wave overtopping conditions. The dike will not fail after one wave, but will be weakened more and more by the multiple incoming waves until the grass sod fails.

PART III -

CRITICAL VELOCITY OF GRASSED SLOPES

8 Sod pulling test and Cumulative Overload Method

In the previous chapters the results from the sod pulling tests have been discussed along with the insight gained during these tests. This chapter provides the link between the sod pulling test results and the critical velocity in the Cumulative Overload Method. First the results per location will be discussed, where the type of maintenance will have an important role. The influence of the saturation is already covered in Chapter 5.4, but a further elaboration will be given in this chapter. After that the Cumulative Overload Method will be discussed, in which the parameters of the overtopping waves are included. In Section 8.4 the critical velocity will be determined. In the section thereafter, the critical velocity in the overload method and the results from the sod pulling tests will be combined in order to answer the main question in this thesis. This will be done by comparing the determined critical velocity from the wave overtopping simulator tests with the calculated values in this thesis. Lastly, the discussion of the found relation is provided and a systematic plan to determine the strength of a grass sod during wave overtopping.

8.1 Strength of Boonweg and Millingen

In this section the results from the sod pulling test will be summarized per location. Here the influence of the maintenance type on the strength of the grass sod will become visible. This influence is compared with the (old) theoretical influence determined in Paragraph 3.1. The goal is to determine the strongest grass sod on the tested maintenance types and the agreement with the theory. The Boonweg is a perfect location to test the influence of different maintenance on a grass sod, because four types of maintenance are implemented on the same dike section of 50 metres.

The different maintenances types at the Boonweg and Millingen apply per year

Boonweg 1   Periodic grazing with low sheep intensity, with 70kg N/ha fertilization;
Boonweg 2   Twice intensive grazing, one time hay-making, no fertilization;
Boonweg 3   No grazing, twice hay-making, no fertilization;
Boonweg 4   First haymaking, then grazing, followed by an extra hay-making, no fertilization;
Millingen   No grazing, twice hay-making, no fertilization.

Tests by Alterra in 2008 revealed that the root densities of all the Boonweg dike sections are qualified as good. It is assumed that this has not changed the previous years, since the maintenance is kept identical. Also some tests were carried out with the new simple field method, separating the soil sample into smaller pieces. All these tests resulted in a closed rooting qualification.

Based on this information and the available theory of influence of maintenance on the quality of the grass, the locations are expected to have the following strength:

- Boonweg 3 and Millingen (H3: Many species in Hay-land): Good quality grass
- Boonweg 1, 2 and 4 (M2: Moderate species in Meadow): Moderate quality grass

This is also the representative for the expected strength of the grass during the tests.

The strength of the intact grass sod is calculated by means of the practical approach. All the tests at one location are plotted in Figure 38 in the same colour, where the thick line represents the average of the respective section.
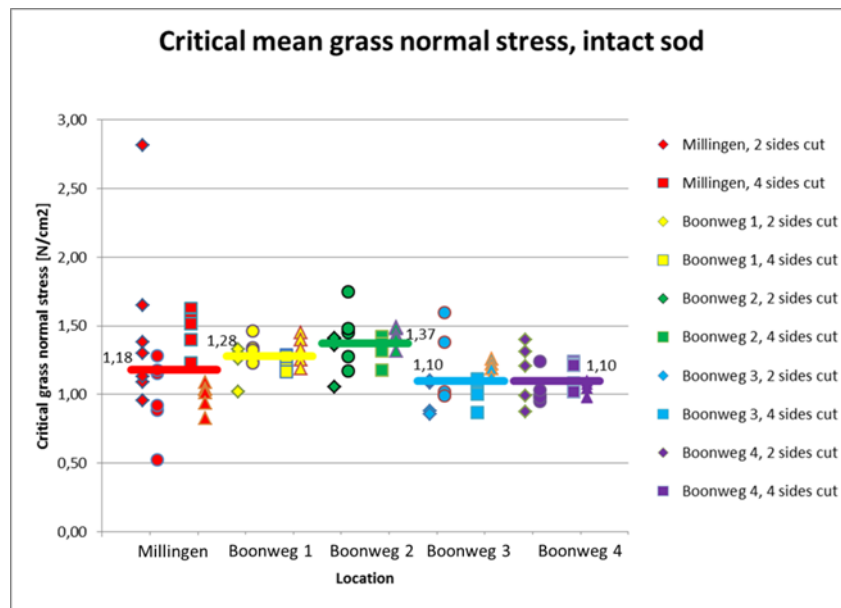
Figure 38 - Average critical mean stress per location

Figure 38 shows that the strength of the grass on Boonweg 2 was on average the strongest during testing with the sod pulling device. Boonweg 1 is also one of the stronger sections. Millingen is on average lower than Boonweg 1 and 2, but higher than Boonweg 3 and 4. The results from Millingen are more scattered around the average compared to the other sections. Boonweg 3 and 4 are in the same order of strength, but are the weakest of the tested sections.

These results are not in line with the expectations based on the maintenance type of the different locations. Millingen and Boonweg 3 have the same type of maintenance, which should result in a good quality grass layer. However, the Boonweg dike section 3 is one of the weaker areas, whereas Millingen is on average stronger. The difference between these sections could be possibly caused by the facing of the slope (Millingen North East, Boonweg South), the salt water intrusion at the Boonweg or the weather during testing, see also Chapter 2.2 and the next paragraph. Not enough data are available to give a more conclusive explanation for the differences. This can be investigated in further research.

Solely assessing the data and therefore not taking the different influences (weather, salt intrusion and slope facing) into account, the conclusion is that the maintenance types on Boonweg 1 and 2 provide a strong grass sod. The maintenance on Millingen and Boonweg 3 and 4 result in a grass sod with moderate strength. However, this is not in line with the previously accepted theory of the influence of the maintenance on the grass strength. It is important to do extra tests on different sections with certain types of maintenance to check this influence and which maintenance type should preferably be used on dikes in the Netherlands. But it can be concluded from the tests in this thesis that the older theory of maintenance type is not always applicable for the strength of a dike section. This was also concluded during the wave overtopping simulations in 2008 (Infram, 2008).

Discussion
The weather has an influence on the results of the tests. When testing on different days, it will surely cause a deviation in the results due to changing of weather conditions. When the tests are also carried out at different locations, the amount of variables is significant. It is difficult to pick out one of the variables as governing, since it is hard to exclude one variable from the others. One would expect that the same type of maintenance results in the same order of strength. However since Boonweg 3 and Millingen have the same maintenance type, more factors influence the strength. The facing of the dike and salt intrusion are examples of these factors. But also the rainfall over the last few weeks

may result in lower suction pressures between the aggregates in the subsoil (after artificial watering for two hours), which can result in a reduction of the forces required to pull out a sod.

Grazing seems to have a positive influence on the strength of the grass. This results, besides the direct effects of the sheep, in less insects and less small animals like mice. These small animals dig tunnels and caves in the sod and break roots in the process. The grass sod also becomes more compact by the grazing, which results in less spongy behaviour of the sod during wave overtopping (Infram, 2008).

8.1.1 Influence of saturation

In Chapter 5.4 the influence of the saturation was discussed. However, the governing parameter was the measured maximum force. The force of the unsaturated tests was compared with the measured force of the regular (saturated) tests. With the derived practical method it is possible to compare the two situations in terms of critical grass normal stresses. The values are calculated with the practical approach and are plotted in Figure 39. In this figure the critical mean grass normal stress is plotted on the vertical axis, where the horizontal axis represents the different locations and tests. The results from Millingen are plotted in red, Boonweg 1 in yellow. The left diamond shaped points per location (given as U) show the tests performed under unsaturated conditions, the right smaller dots (S) show the regular tests under saturated conditions.
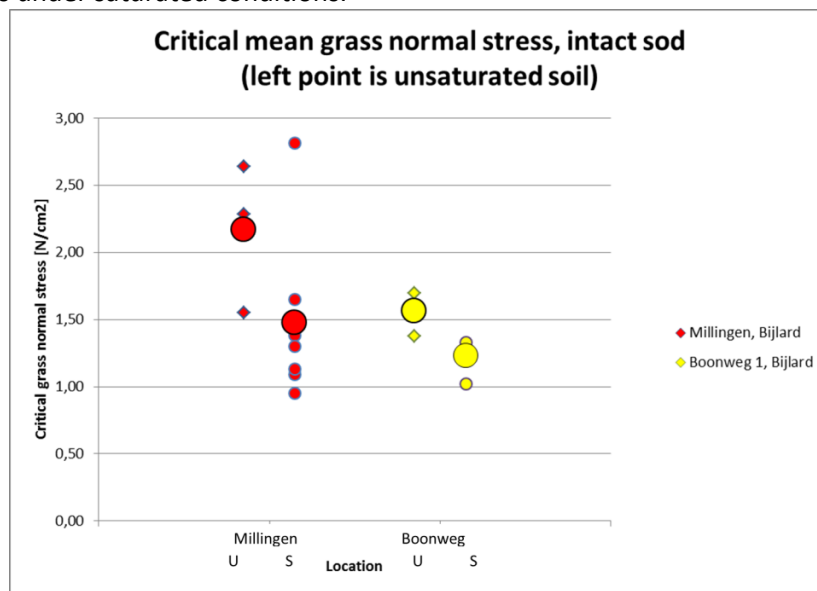
Figure 39 - Influence of saturation on the critical stress of intact sod

Figure 39 clearly shows that the influence of the saturation is still present when the forces are rewritten into stresses. With the new values the influence of the suction pressures can be determined. At Millingen there was no rain the past two weeks and it was sunny day during the tests. This resulted on average in a difference of 0.7 N/cm2 (or 7 kN/m2) which could be contributed towards the suction pressures. At the Boonweg, this difference is smaller on a rainy and clouded day. But the difference was still in the order of 0.3 N/cm2 (or 3 kN/m2), which is a significant difference and cannot be neglected.

This influence is not as high as assumed in theory, where values up to 50 kN/m2 of suction pressure in the clay layer are given during nice weather conditions (Hoffmans, 2012). The measured values are not close to the theoretically assumed values, but it is possible that there is a difference between the suction pressure of clay and the suction pressure of a grass sod. Furthermore, the force transmission of the suction pressures during the sod pulling tests are not completely understood, so it could be that not all the suction pressures have to be compensated in order to lift the sod. But it is clear that the suction pressures have significant influence on the strength of the grass sod, therefore it cannot be neglected during tests. It is best to execute the sod pulling tests under saturated conditions in order to simulate the wave overtopping conditions during storm events.

8.2   Wave overtopping processes

The next sections will discuss the wave overtopping processes which will be used to determine the load on the grass sod. This can be seen as an introduction for the theory used with the wave overtopping simulator and the Cumulative Overload Method.

Wave overtopping is generally described by an average wave overtopping discharge. However, this discharge does not make a distinction between mild and severe wave conditions. Severe (sea) wave conditions have in general only a few waves overtopping the crest, but these waves have a large volume. The milder (river) wave conditions result in a lot of waves with a small volume overtopping the crest. However, both wave conditions can give the same average wave overtopping discharge. Since there is a distinct difference in the loads caused by these two wave climates, it is important to find a parameter that can describe this difference in behaviour. This is possible with the Cumulative Overload Method.

The severity of the overtopping waves can also described by the significant wave height (H_s), where a larger significant wave height results in a more severe wave overtopping climate. In this section the distribution of overtopping waves will be discussed first, after which the wave parameters from the wave overtopping simulator will follow.

8.2.1   Distribution of overtopping waves

The crest height of a dike can be determined on the basis of an allowable average wave overtopping volume. Severe wave overtopping may damage the crest and landward side of the dike. The mean overtopping discharge and the distribution of the overtopping wave volumes describe the wave overtopping in general. However, each overtopping volume has a certain flow depth, velocity and duration. The wave overtopping simulator simulates the overtopping wave tongues at the crest of the dike, based on certain volumes of water per overtopping wave condition. With these wave overtopping simulations the Cumulative Overload Method is developed in order to determine the erosion of grassed slopes. This method uses the critical velocity of the grass as a strength factor, which may be determined with the results from the sod pulling tests.

The mean overtopping discharge is determined on a number of overtopping waves and not as a constant flow. There is a certain distribution for these waves, which can be generated by the wave overtopping simulator to overtop the crest of the dike. The magnitude of the wave overtopping volume is a key design parameter for determining the crest height of dikes. There are empirical relations developed in recent years which describe the wave overtopping processes. When wave conditions and crest freeboard remain constant, the wave overtopping can be described by a mean discharge (q) and a distribution of overtopping waves (P_V). Recent studies show that the forces exerted on the grass sod depend largely on the distribution of front velocity of the overtopping wave. This section is from the papers of Van der Meer *et al.* (2010) and Hughes *et al.* (2012).

The average wave overtopping discharge q is simply the total volume of overtopped water (per unit length) in a certain duration, divided by this duration. Not all overtopping waves are of the same size. There will be a certain number of overtopping waves that produce a distribution of overtopping wave volumes. This distribution is characterized by a lot of small waves and a few larger waves (EurOtop, 2007). This distribution can be described by a two parameter Weibull distribution, where there is a difference between a cumulative probability (Equation 11) and a percentage exceedance distribution (Equation 12).

$$P_V(V_i \leq V) = 1 - \exp[-(V/a)^b] \qquad (11)$$

$$P_{V\%}(V_i \geq V) = \exp[-(V/a)^b] * 100\% \qquad (12)$$

Here is P_V the probability that an individual wave volume (V_i) will be less than a specified volume (V) and $P_{V\%}$ is the percentage of wave volumes that will exceed a specified volume. The two parameters in the Weibull distribution are the dimensional scale factor a, which normalizes the distribution

(Equation 13) and dimensionless shape factor *b*, which defines the extreme tail of the distribution (Equation 14).

$$a = 0.84\, T_m \frac{q}{P_{ov}} = 0.84\, T_m\, q\, \frac{N_w}{N_{ow}} = 0.84\, q\, \frac{t}{N_{ow}} \qquad (13)$$

$$b = [\exp(-0.6\frac{R_c}{H_{m0}})]^{1.8} + 0.64 \qquad (14)$$

In this equation represents T_m the mean wave period, N_W the number of incident waves, N_{ow} the number of overtopping waves and *t* the duration of the storm. Overtopping waves occur random in time, which also applies for the volumes of these overtopping waves. The factor 0.84 in the dimensional scale factor is only valid for infinite number of overtopping waves. When this is not the case, the factor should be increased in order to comply with the condition from Equation 15.

$$\sum_{i=Nw}^{i=1} V_i = q\, t \qquad (15)$$

When the value is not adjusted, the total summation of the overtopping wave volumes will be less than the calculated value from the mean discharge over time. In Figure 40 the adjustments in this factor are plotted as a function of the number of overtopping waves (Van der Meer *et al., 2011)*. Only if the number of overtopping waves reaches 1000 or more, the value 0.84 may be applied.
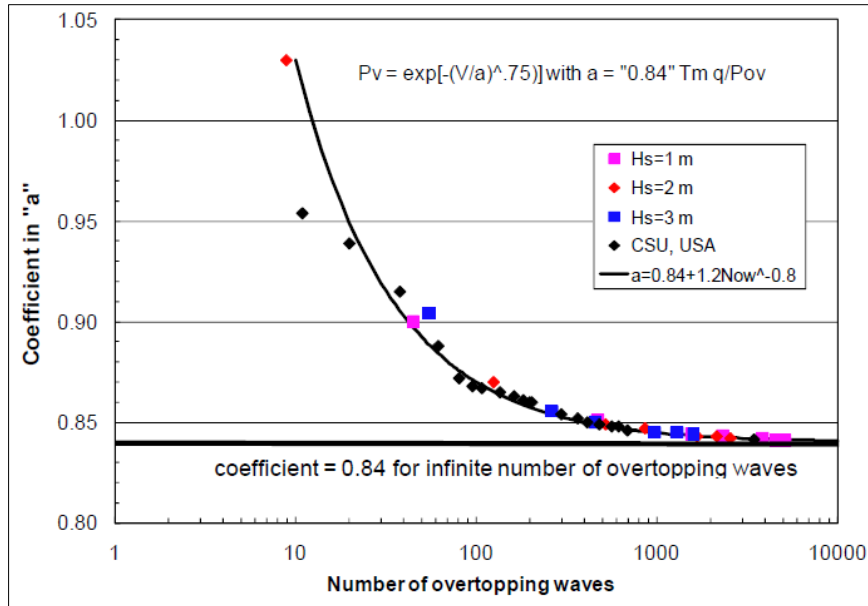
Figure 40 - Alpha coefficient as function of number of overtopping waves (Van der Meer 2011)

The dimensionless scale factor b depends on the relative crest freeboard (R_c) compared with an estimation of the significant wave height (H_{m0}). The value for b of 0.75 has been applied for quite some time, which is valid for $\frac{R_c}{H_{m0}} > 1.5$. Figure 41 (Steendam, 2013) shows that with a smaller crest freeboard the *b* value increases significantly. This will lead to a more gentle distribution of the overtopping wave volumes.
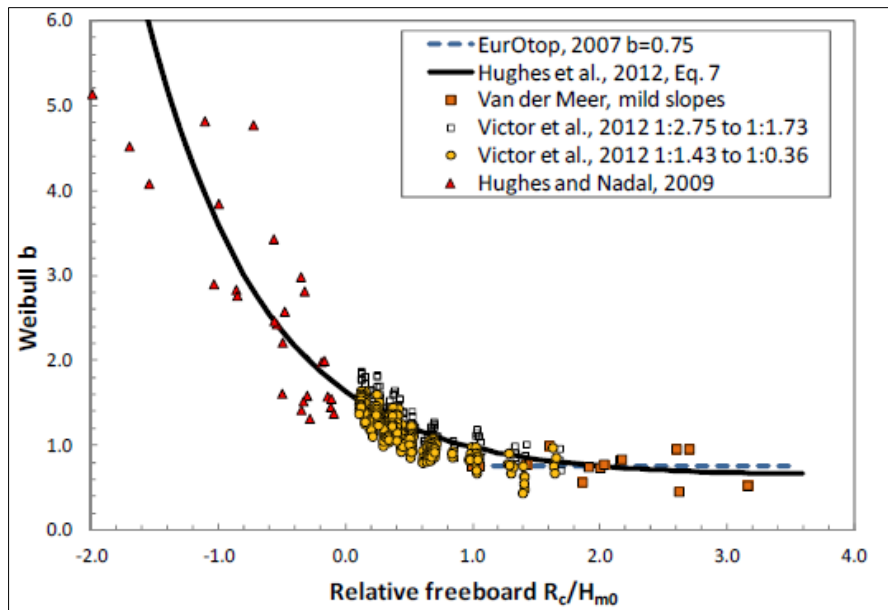
Figure 41 - Shape factor b as function of crest freeboard (Steendam 2013)

In addition to reproducing the distribution of individual overtopping wave volumes and the average overtopping discharge, another important goal of wave overtopping simulation is to approximate the hydraulic flow parameters associated with individual overtopping wave volumes. Of particular importance are the maximum flow thickness, maximum velocity and maximum discharge at the leading edge of the wave. Also the duration of overtopping associated with each wave volume is important. These parameters are discussed in the next section.

8.2.2 Wave parameters

With the distribution of the overtopping wave volumes determined, the wave parameters will be discussed in this section. This paragraph is from a paper of Van der Meer *et al.* (2010) and is shown here to give insight in the relations between the different wave parameters used for the wave overtopping simulator and the Cumulative Overload Method.

For the wave overtopping simulations, empirical relations have been used to determine the flow depth (Equation 16) and flow velocity (Equation 17) as a function of the overtopping wave volume. These relations are found by curve fitting the measurements from the wave overtopping simulator. The relations are established for a slope of 1:3.7 (upper part) to 1:5.2 (lower part of the dike). The flow velocity of the overtopping wave is an important input parameter in the Cumulative Overload Method, since this will be used as the load factor of the overtopping wave.

$$h = 0.133 \, V^{0.5} \tag{16}$$

$$u = 5.0 \, V^{0.34} \tag{17}$$

Hydraulic measurements from a steeper (1:2.4) slope resulted in a somewhat different curve fitting for the velocity at the crest of the dike. The velocities of a steeper slope are a bit lower at the crest, but in the same order of magnitude, see Equation 18 (Steendam, 2012).

$$u = 4.5 \, V^{0.30} \tag{18}$$

In this equation *h* represents the maximum flow depth at and directly behind the crest. Further down the slope the depth decreases slightly. The maximum flow velocity of the overtopping wave is represented by *u* and is almost equal to the depth average velocity. There is no large difference between the velocity at ground level (boundary layer) and at the top of the flow when the velocity is smaller than 3 m/s. For larger flow velocities this difference is present, since the maximum velocities near the ground level are around 5 m/s, while the top of the flow measures velocities up to 9 m/s. However, just above the boundary layer (which is only a few centimetres thick) there is not a large

difference in the flow velocity with respect to the top of the flow. At 5 mm from the ground level the flow velocity is already about 60-70% of the velocity at the top of the flow (see Van der Meer *et al.* (2010).

Since the flow thickness decreases over the slope, the flow velocity must increase. Otherwise the overtopping wave volume would not be constant. The increase of the velocity over the slope depends on the steepness of the slope. In order to comply with this acceleration, Equation 18 for the velocity of the overtopping waves is adjusted, by including an acceleration factor α, see Equation 19 (WTI, 2015).

$$u = \alpha * 4.5\, V^{0.30} \tag{19}$$

The acceleration factor depends on the steepness and the distance along the slope and is based on Schüttrumpf (2005). In Figure 42 the acceleration factor is plotted as a function of the distance along the slope. The coloured lines indicate various slopes, where the solid line is used for a starting velocity at the crest of 4 m/s and the dashed line for 6 m/s.
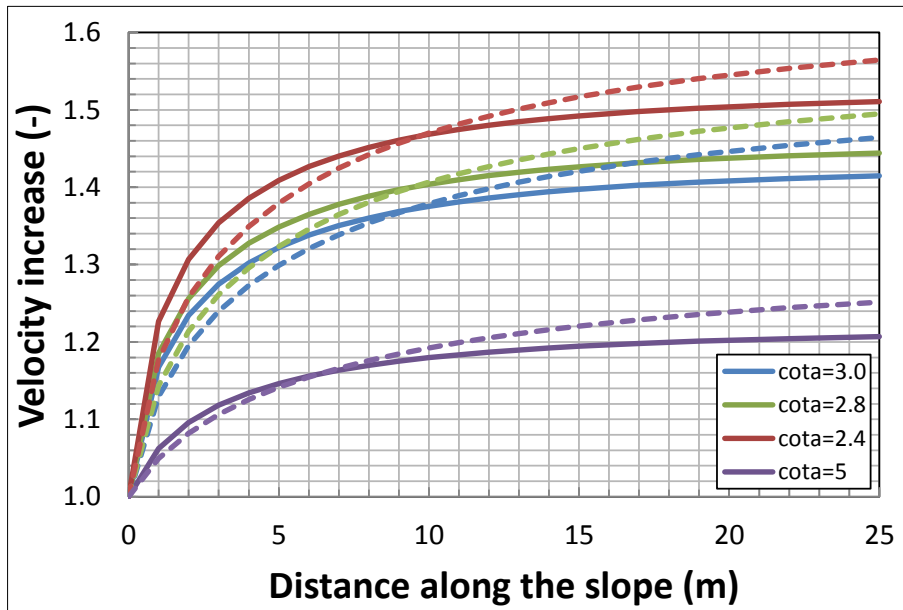
Figure 42 - Acceleration factor as function of the slope length and steepness (WTI, 2015)

The wave overtopping duration (T_{ovt}) is also determined during the wave overtopping simulations with some curve fitting for the smoother slopes, see Equation 20. It is hard to determine the duration for small overtopping wave volumes, since there will be some water present in the boundary layer after the wave has passed. This results in some inaccuracies in the duration for small volumes. However, when the overtopping wave volumes increase the empirical relation fits the encountered duration quite well.

$$T_{ovt} = 4.4\, V^{0.3} \tag{20}$$

The empirical coefficients in all these equations are not dimensionless. They compute different wave overtopping quantities as a function of the wave overtopping volume. However, there is a relation between all of them. All empirical equations combined give all the variables in the mass balance. When assumed that an overtopping volume has a triangular shape over time over the slope, the physical relation will lead to Equation 21.

$$V = \frac{1}{3}\, h\, u\, T_{ovt} \tag{21}$$

The three empirical relations combined results in Equation 22 for smoother slopes.

$$V^{1.1} = 0.38\, h\, u\, T_{ovt} \tag{22}$$

Both equations are almost equal except for the power coefficient of the overtopping volume. But since the second equation is based on three different curve fitting relations, the combination fits the mass balance quite well. Especially for overtopping volumes around 1 m³/m there is a good correlation.

8.3   Cumulative Overload Method

The wave parameters have been determined in the previous paragraph. Therefore it is possible to determine the effect of overtopping waves on a slope. When the overtopping waves runs over the crest onto the landward side of the slope, damage will start to develop over time. There are different stages of damage, where failure of the dike is the easiest to define. When the top layer of the dike is eroded, the core of sand will become visible. This core has almost no resistance against the overtopping waves, which leads to rapid increase of erosion of the core. This will quickly lead to failure of the dike. Therefore it is assumed that when the sand core is reached, the dike section has failed. It is possible to define more stages of damage during wave overtopping, such as the first damage to the sod. A disadvantage of this criterion is that a small hole can already exist in the top layer, even before testing begins. Also a very weak spot in the grass layer can quickly result in a small hole. Therefore it is preferred to use various damage locations as a damage factor instead of start of damage. This implies that one small weak spot is less important over the entire section. However, failure is still the best and most constant stage of damage, which is also easiest to define.

Another possibility is that the dike section did not fail during the storm. This can also be used as a damage criterion. In short, the following criteria will be used, of which examples are shown in the Figures 43a to 43d (Van der Meer *et al.,* 2010).

-   First damage (Figure 43a)
-   Various damaged locations (Figure 43b)
-   Failure (Figure 43c)
-   Non-failure after testing (Figure 43d)

Figure 43 a,b,c,d - Various failure criteria for overtopping simulator tests: First damage (a); Multiple open spots (b); Failure (c) and non-failure after testing (d) (Van der Meer, 2010)

There are different ways to determine the erosional development. Dean *et al.* (2010) worked on erosional equivalence with a time dependent factor in the formulations. The erosion could be described with an excess velocity (u), an excess of shear stress (u^2) or as an excess of work (u^3). The velocity of the overtopping waves is an important parameter, which can be compared with a critical velocity (U_c). However, this research was carried out for continuous overflowing water over the dike, which is not completely comparable with wave overtopping. The time factor of overtopping waves is not that important, since it is a short interval (1-3 seconds) and the wave overtopping velocities are higher. This decreases the time influence further, so the duration can be excluded from the equation for erosion during wave overtopping. The theory of shear stress with a threshold was taken as a basis for development of erosion (Hoffmans *et al.*, 2008). This theory was confirmed during the wave overtopping simulation tests at the Vechtdijk, where smaller wave volumes did not contribute to the development of damage. This threshold is given as a critical velocity (U_c) which must be exceeded before damage can start to occur (Van der Meer *et al.*, 2010). This leads to Equation 23 called the "Cumulative Overload Method".

$$D = \sum_{i=1}^{N} (\alpha_M U^2 - \alpha_s U_c^2) \qquad for\ \alpha_M U^2 > \alpha_s U_c^2 \tag{23}$$

In this equation is D the damage factor in m²/s² and α_M a load factor for an increase in the velocity of the overtopping wave (U). Furthermore, α_s is a strength factor for a decrease in the strength of a grass sod, where the strength of the grass sod can be expressed as a critical velocity (U_c). Since the distribution of the overtopping wave volumes and the velocity per overtopping wave volume is known, it is possible to calculate the number of tests required until a damage criterion is reached. This does depend on the critical velocity used as a threshold.

The damage factors (D) in the Cumulative Overload Method have been determined during the wave overtopping simulation tests at the Vechtdijk near Zwolle (Overijssel). From these tests the following damage factors have been determined after recalibration (WTI, 2015).

Start of damage $\qquad \sum(U^2 - U_c^2) = 1000\ m^2/s^2$
Various open spots $\qquad \sum(U^2 - U_c^2) = 4000\ m^2/s^2$
Failure $\qquad\qquad\quad \sum(U^2 - U_c^2) = 7000\ m^2/s^2$

It appeared during later wave overtopping simulator tests that transitions and objects on the dike prove to be more vulnerable to damage, therefore an amplification factor (α_M) is added for the increase of the actual velocity due to the transition or object (SBW, 2012). The amplification factor is larger than 1, therefore more waves will contribute to the damage on the slopes. The factor can be calculated with two different equations, one for obstacles and another one for transitions. Equation 24 is used for obstacles. This formula uses the increase of the force on the grass sod around an obstacle, as a percentage of the force acting on the grass sod as if there was no obstacle. Equation 25 can be used to determine the load increase due to geometrical transitions, for example the transition from the dike slope to a horizontal berm. At this transition the water wants to follow its downward direction. This shift in direction of the water will lead to higher forces on the grass sod. This load increase depends on the change in slope angle at the transition. Both formulations are from the paper of Steendam *et al.* (2014).

$$\alpha_M = \frac{F_M}{F} = 1 + \frac{dF}{F} \tag{24}$$

$$\alpha_M = 1 + \sin(\frac{1}{2}\theta) \tag{25}$$

In these equations F represents the shear force under flow conditions on a regular slope, F_M the maximum shear force and dF the increase of shear force at the obstacle. The steepness of the slope is given as θ (in degrees).

Another problem with objects and transitions on slopes is that they also reduce the strength of the grass near that object or transition. Since the first term in the Cumulative Overload Method represents the load on the grass and the second term the strength of the grass, another factor was added in order to deal with this decrease in strength. This is given by the α_s factor, which is smaller or equal to 1, since obstacles and transitions decrease the strength of the grass. It can be for instance because of the additional difficulty of mowing near these places or the placement of stones underneath the sod near the toe or fence. However, the direction in which the grass is hindered to grow due to the obstacle is more important. When there is a vertical transition at one side of the grass, the roots cannot penetrate the soil in that direction. This leads to one less side wall which can resist the uplifting force. This influence can be calculated with the results from the sod pulling tests, using Equation 26 (Deltares, 2013).

$$\alpha_s = \frac{1.5F_2 - 0.5F_4}{2F_2 - F_4} \tag{26}$$

During the tests in this thesis, the transitions in a slope are not tested with the sod pulling device. However, due to the similarities between the condition 2 and condition 4 tests, the influence of one less side wall available to the sod can be estimated with Formula 26. This is also done by Deltares for other tests and resulted in a value for α_s of 0.9. When the same calculation is made for the tests performed at Boonweg and Millingen, it results in a factor between $0.82 - 0.95$ with an average of 0.86. So the results are comparable to the earlier research by Deltares.

8.4   Determining the critical velocity

Different stages of damage have been determined with the Cumulative Overload Method, but the critical velocity of the grass requires further elaboration. The current methods of determining the sod quality from Chapter 3.3 divide the grass into the groups closed, open and fragmented grass sod. Research has already been conducted in order to link the three groups towards a critical velocity. This is based on various parameters per quality and not as an exact science. Furthermore there is not yet a link between the sod pulling tests and the critical velocity formula.

In this section a summary of the derivation of the critical velocity formula is given. This is copied from a combination of two papers and a book written by Hoffmans (2008, 2010 and 2012). It is shown in this report, because it provides key insights in understanding the critical velocity formula. The full derivation of the sod quality towards the critical velocity is given in Appendix D.

8.4.1   Strength of the soil

The strength of the grass sod can be described best by combining the Mohr-Coulomb equation and the Turf Element Model. The Mohr-Coulomb describes soil failure in terms of shear- and normal stresses along a sliding plain. A parameter for the strength of the roots (Equation 28) is inserted in the formula in order to use Equation 27 for grass strength.

$$\tau_s = c_e \cos \phi_e + c_r + (\sigma - p_w) sin\phi_e \tag{27}$$

With

$$c_r = 1{,}2\sigma_{root} \frac{A_r}{A} \tag{28}$$

In this equation τ_s describes the soil shear stress, c_e the effective soil cohesion, p_w the pore water pressure, σ the soil normal stress and ϕ_e represents the effective angle of internal friction. The strength of the roots is represented by the root cohesion c_r. In the Equation 28 is the factor A_r / A known as the Root Area Ratio (or RAR).

A problem with the estimated c_r and σ_{grass} is that the equation assumes that all the roots break and that they do it simultaneously. From field tests it has become clear that this is not the case. Roots break at different elevations and some roots are pulled out of the remaining sod. Because of this, the outcomes of the equations could lead to an overestimation of c_r and σ_{grass}.

The Turf Element Model tries to link the strength and the load on the grass sod together. This model is based on a saturated turf aggregate with the dimensions of a cube, see Figure 44. On this cube two

types of forces can be distinguished: the load forces due to pressure fluctuations perpendicular to the grass cover (caused by overtopping waves for example) and the strength factors of the soil.
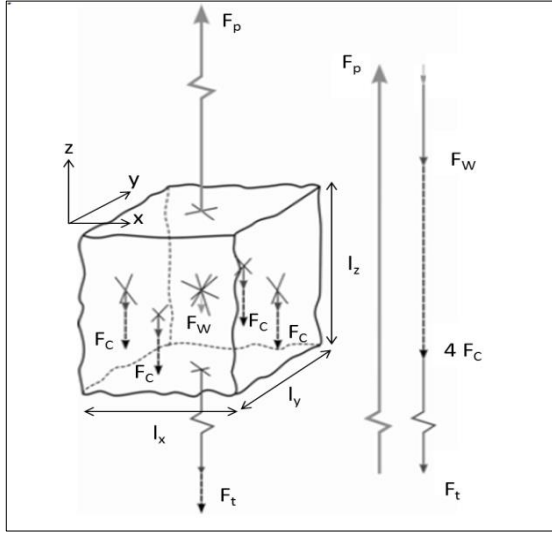

In Figure 44 F_p represents the maximum lift force and F_w the submerged weight of the soil. F_c is the critical friction force acting on one side, which depends on the rupture strength of clay $C_{clay,\ c}$ and mean grass shear stress $\tau_{grass,\ c}$. Furthermore, F_t is the critical mean tensile force on the bottom plane. The maximum lowering of the local pressure caused by eddies in the overtopping wave is represented by p_m.

When particles start to move, horizontal loads are usually considered. When the shear stress reaches the critical mean bed shear stress τ_c, turf aggregates will start to move. The movement of these particles can best be described with the critical Shields parameter Ψ_c. This parameter has a value between 0.03 and 0.06 for larger particles in turbulent flow.

Figure 44 - Turf Element Model schematization with different forces acting on a cube representing the sod (Hoffmans, 2012)

Since grass sods can easily resist compression forces only tensile stresses will lead to failure of the sod. The submerged weight of the soil and the strength of the clay are in the order of 5% of the strength of the grass and can therefore be neglected for simplicity. This results in Equation 29.

$$\tau_0 \geq \tau_c = \Psi_c \left[4\, \tau_{grass,c} + \sigma_{grass,c} \left(-\lambda_{ref}\right)\right] \tag{29}$$

The strength is determined by the roots in the four sides and the bottom of the cube. Since grass roots have the same properties in the length direction, the shear strength (side roots) and the tensile strength (bottom roots) can be expressed relative to each other. The exponential decrease of roots over the depth is taken into account and combined with the formulations for the estimation of strength of an intact sod by Hoffmans, leading to Equation 30.

$$\tau_0 \geq \tau_c = \alpha_{grass,\tau}\, \Psi_c\, \sigma_{grass,c}\, (0) \tag{30}$$

With

$$\alpha_{grass,\tau} = 2.9 \tag{31}$$

8.4.2 Turbulence

The strength of the grass has been determined, but the loads on the grass sod still have to be investigated. When the overtopping wave is rolling down the slope considerable turbulence will occur due to the irregularities in the sod. When small aggregates are washed away, these irregularities will even increase further, leading to more turbulence. The bed roughness is characterized by the Chézy coefficient (C) in Equation 32.

$$U_0 = C\sqrt{R_h S_b} \tag{32}$$

Where U_0 is the depth averaged flow velocity, R_h the hydraulic radius equal to the flow depth and S_b is the slope of the dike. The depth averaged relative turbulence intensity (r_0) is defined by Equation 33.

$$r_0 = \frac{\sqrt{k_0}}{U_0} \tag{33}$$

In this formulation is k_0 the depth averaged turbulent kinetic energy in all directions. This formula can be simplified (Graf 1998) towards

$$\sqrt{k_0} = \alpha_0 u_* \tag{34}$$

In this equation α_0 is a constant with a value of 1.2. The relative turbulence can be rewritten, where u_* is the bed shear velocity given as $u_* = \sqrt{g R_h S_b}$, into Equation 35.

$$r_0 = \frac{\alpha_0 u_*}{U_0} = \frac{\alpha_0 \sqrt{g}}{C} \tag{35}$$

This results in relative turbulence intensity between 0.1 and 0.3, assuming a maximum flow velocity of 8 m/s and flow depths between 2 and 40 cm.

8.4.3 Critical velocity

The loads and the strength parameters have been determined, so it is possible to combine them into an equation for the critical velocity. When assumed that the overtopping wave generates a hydraulically rough flow and the start of motion of sod particles is given as $U_0 = U_c$, the critical depth-averaged velocity of fully saturated grass can be calculated with Equation 36.

$$U_c = \alpha_{grass,U} \; r_0^{-1} \sqrt{\frac{\Psi_c \; \sigma_{grass,c}(0)}{\rho}} \tag{36}$$

With $\alpha_{grass,U} = 2.0$

However, since the above equation assumes a fully saturated state of the sod, a small adjustment should be made in order to incorporate the saturation of the sod. The saturation will increase over time during storm conditions, to which the suction pressures will reduce to zero. The pore water pressure (p_w) represents the suction pressure in the roots and has a negative sign (for example -10 kN/m^2), which results in an increase in the critical velocity of the slope, see Equation 37. At the moment the top layer is fully saturated, p_w is equal to zero. This is most likely during storm conditions, which is often accompanied by heavy rain leading to a fully saturate sod. However, in summer time it is possible that there are high river discharges leading to the overtopping waves. This can be caused by storm conditions further inland, while it has not rained on the location itself. During these conditions, the top layer of the dike is not fully saturated, resulting in suction pressures in the sod. So the suction pressure must be included in the equation for the critical velocity as long as the soil is not fully saturated.

$$U_c = \alpha_{grass,U} \; r_0^{-1} \sqrt{\frac{\Psi_c \; (\sigma_{grass,c}(0) - p_w)}{\rho}} \tag{37}$$

This formula indicates that the critical velocity is proportional to the square root of the grass normal stress, which can be determined with the sod pulling tests.

8.5 Sod pulling test and critical velocity

In this paragraph the relation between the sod pulling tests and the critical velocity determined from the wave overtopping simulations will be investigated. Firstly, some small adjustments will be made in the critical velocity formula, after which an extra damage factor for the Cumulative Overload Method will be introduced. Thirdly, a distribution for the strength of the intact grass sod will be determined in order to calculate the weakest spots on the slope. In the last section everything will be combined to investigate the relation between the sod pulling tests and the wave overtopping simulations.

8.5.1 Adjustments critical velocity formula

In the previous paragraph a relation was provided for determining the critical velocity (U_c) as a function of the relative turbulence (r_0), the shields parameter (Ψ_c), the pore water pressure (p_w) and the critical grass mean normal stress at ground level ($\sigma_{grass,c}(0)$) with Equation 37. In this section each of the parameters will be discussed separately, except for the critical grass mean normal stress which will be further elaborated in Section 8.5.3.

Shields parameter

The shields parameter is based on the transport of loosely packed sand on a river bed (Shields, 1936). This is based on the assumption that the movement of particles is caused by a shear stress (or bed shear velocity) on the particle. This parameter has a value between 0.03 and 0.06 for larger particles in turbulent flow. Later research by Emmerling (1973) showed that the movement of particles was not caused by the shear stress, but by the fluctuating pressure forces acting on the particle. When a suction pressure acts on the sample, it will be lifted from the bed and transported, see also Appendix D. These suction pressures can reach values up to 18 times the bed shear stress. If the porosity (n) is taken into account, it can be rewritten into a Shields parameter, leading to Equation 38.

$$\Psi_c = \frac{1}{18} * (1 - n) = \frac{1}{18} * (1 - 0.4) = 0.033 \tag{38}$$

This is comparable to the value of the Shields parameter for particles in turbulent flow. Both methods cannot be compared with the erosion (or movement) of the grass sod during wave overtopping conditions, but give an indication of the value. This adjusted Shields parameter is assumed to be constant for grass erosion in general, with a value of 0.03, which is also used by Hoffmans (2012). Since it is assumed not to vary per location, it can be removed as an input parameter from the equation and added to the $\alpha_{grass,U}$ factor in order to get the more practical Equation 39.

$$U_c = \alpha_{grass,c} \ r_0^{-1} \sqrt{\frac{(\sigma_{grass,c}(0) - p_w)}{\rho}} \tag{39}$$

With

$$\alpha_{grass,c} = \alpha_{grass,U} * \sqrt{\Psi_c} = 0.34 \tag{40}$$

Pore water pressure

The pore water pressure remains in the equation, since suction pressures can result in much higher critical velocities. However, during the wave overtopping simulator tests the ground becomes saturated over time. At the beginning of the tests only small (low velocity) waves run over the slope, resulting in (almost) no damage, but decrease the suction pressures. When the governing wave conditions overtop the crest during the simulation the ground is fully saturated and the pore water pressure is zero. However, during governing river dike conditions the ground might not be completely saturated when the high water waves overtop the crest. This unsaturation of the sod results in suction pressures, which increase the strength of the sod. Therefore the p_w factor cannot be neglected in the equation.

Before the sod pulling tests start the ground is artificially watered, which leads to zero suction pressures in the soil. During the representative wave overtopping simulations and the sod pulling tests there are no suction pressures left in the sod, therefore this factor is set to zero in this thesis.

Relative turbulence intensity

The relative turbulence intensity plays an important role in the equation for the critical velocity. This factor is normally between 0.10 and 0.20 for overtopping waves on a slope. The further down the slope, the higher the velocity on that section and the lower the relative turbulence. During the wave overtopping simulations it was noticed that most of the damage occurred at the bottom half of the slope. Here the acceleration factor (see Section 8.2.2) is in the order of 1.5, therefore a low relative turbulence should be applied. A value close to 0.10 should be used as an estimation, but the velocity could be a bit higher in theory (less turbulence). The factor is fitted on 0.12 for the damage found on the tested locations. When damage is found higher up on the slope, the relative turbulence intensity can be increased up to a maximum of 0.20 for damage at the crest of the dike.

The value of 0.12 is also used for the Boonweg 1 and 2 where there was no sign of damage over the slope. During wave overtopping simulation tests at other locations most of the damage started at the downward side of the slope, which is therefore also expected for the Boonweg sections 1 and 2.

Since the velocities during the wave overtopping conditions over the slope are the same at the locations, the same relative turbulence intensity is used.

The relative turbulence can be related to the Chézy coefficient. When Equation 41 is used, the turbulence can be related to the roughness of the slope.

$$r_0 = \frac{\alpha_0 \sqrt{g}}{C} \tag{41}$$

In these equations is C the Chézy coefficient, α_0 a coefficient with a value of 1.2 and g the gravitational acceleration. When the value of 0.12 is taken for the relative turbulence, the Chézy coefficient is approximately 30 m$^{1/2}$/s. This is inside the range for the roughness of a grass sod, which should be between 25 and 80 m$^{1/2}$/s (Hoffmans, 2012).

8.5.2 Cumulative Overload Method

In Section 8.3 the Cumulative Overload Method is described, where three damage factors are defined: start of damage, various open spots and failure. The question is how a tested section, where no damage occurred during the wave overtopping simulator tests can be used for analyses with the sod pulling tests. This is an important point, since two of the five tested slopes in this research showed no signs of damage during the wave overtopping tests. In order to find a relation between the sod pulling tests and the critical velocities of the slopes, a new factor has to be introduced for no visible damage after testing. When there is no sign of damage on the slope after the complete wave overtopping simulation, none of the damage criterion is met. This means that the damage factor is at least lower than that of failure (=7000 m^2/s^2). However, it is difficult to say how much lower since the section did not fail and there is no knowledge of how close to failure the slope was at the end of the test. On the other hand, the start of damage has not occurred. It could be assumed that the damage factor is lower than 1000 m^2/s^2. How much lower the criterion should be is hard to determine without additional data, but the value of 1000 m^2/s^2 could be used as estimation. So when there is no visible damage, the damage factor should be between 1000 and 7000 m^2/s^2. It is not possible to give a more accurate estimation, also because the first two damage criteria (start of damage and various open spots) are not always visible. For example, at Boonweg 3 and 4 the start of damage criterion was immediately followed by failure of the dike. The bulging mechanism (Chapter 7.1 and Infram 2008) was the first visible damage, but led to failure at the same time. This assumption leads to the following damage factors

No sign of damage	$\sum(U^2 - U_c^2) = 1000 \leq D \leq 7000 \ m^2/s^2$
Start of damage	$\sum(U^2 - U_c^2) = 1000 \ m^2/s^2$
Various open spots	$\sum(U^2 - U_c^2) = 4000 \ m^2/s^2$
Failure	$\sum(U^2 - U_c^2) = 7000 \ m^2/s^2$

This new criterion is used to determine the critical velocity of the two tested sections at the Boonweg 1 and 2 which did not fail. This leads to 2 values between which the critical velocity should be. For the other sections the critical velocity was estimated by Van der Meer in 2015. There was a small error in the previous calculation of the critical velocity for Millingen, which resulted in a too low value (6 m/s). This is now corrected in the data sheet, so that the grass sod in Millingen has the correct critical velocity. Table 14 gives the estimates of the critical velocities for the five tested sections with the wave overtopping simulator.

Table 14 - Critical velocity of different locations based on wave overtopping simulator tests

Location	Uc [m/s]
Millingen	7
Boonweg 1	8 - 9.5
Boonweg 2	8 - 9.5
Boonweg 3	8
Boonweg 4	8

8.5.3 Distribution of the strength of an intact sod

All the sections have am estimation for their critical velocity based on the wave overtopping simulations. This has as benefit that the relation with the sod pulling tests can be compared. When the adjusted critical velocity formula from Equation 39 is used, the $\sigma_{grass,c}(0)$ determined from the sod pulling tests can be applied to this equation. All the sod pulling tests performed in this research resulted in an average critical mean grass normal stress with a standard deviation and a corresponding coefficient of variation. These values are based on all the regular tests carried out at the same location (excluding the 10x10 frame size results) calculated with the practical method presented in this thesis. The standard deviation has been determined in using Equation 42.

$$\sigma = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(x_i - \mu)^2} \quad with \quad \mu = \frac{1}{N}\sum_{i=1}^{N}x_i \tag{42}$$

In Appendix E2 a more elaborate calculation of the standard deviation is given. The final results are shown in Table 15.

Table 15 - Average and standard deviation of the critical mean normal stress per location

	Calculated critical grass tensile stress [N/cm2]		
	μ	σ	Cv
Millingen	1,18	0,27	34%
Boonweg 1	1,28	0,10	8%
Boonweg 2	1,37	0,14	10%
Boonweg 3	1,10	0,17	16%
Boonweg 4	1,10	0,14	12%

During wave overtopping conditions the weakest part of the slope will be the section where start of damage occurs. Therefore for the input value in the critical velocity formula an estimation has to be made for the weakest part of the grass sod. This estimation can be based on a distribution type for the heterogeneity of grass.

Normal distributions are extremely important in statistics and are often used in the natural sciences for real-valued random variables for which the distributions are not known. The normal distribution is useful because of the central limit theorem, which states that under mild conditions the mean of many random variables independently drawn from the same distribution, is distributed normally, irrespective of the form of the original distribution. A problem with the normal distribution is that it can give negative numbers for certain combinations of μ and σ. The critical grass normal stress cannot have a negative value, so this should be avoided. A lognormal distribution cannot reach negative values, so should be used if the normal distribution can results in negative values. In Appendix E1 the data gathered during this thesis is plotted for their relative occurrence. These plots resemble a normal distribution quite well. So a normal distribution is assumed used as distribution type for the measured strength of the grass sod.

In order to find the governing strength of the grass sod, it is assumed that a certain percentage in the normal distribution can represent the weakest parts of the sod. In Figure 45 the normal distribution is shown with certain limits as a function of the standard deviation σ. When the governing points in a normal distribution are in the tails of the distribution, two different limits are often used: The 90% limit, which can be found *1.64 σ* away from the average value and the 95% limit, which is given by *1.96 σ*. These limits are for the two tails, on either side of the average. For grass the weakest parts are governing for damage. This results in a 5% or 2.5% limit respectively.
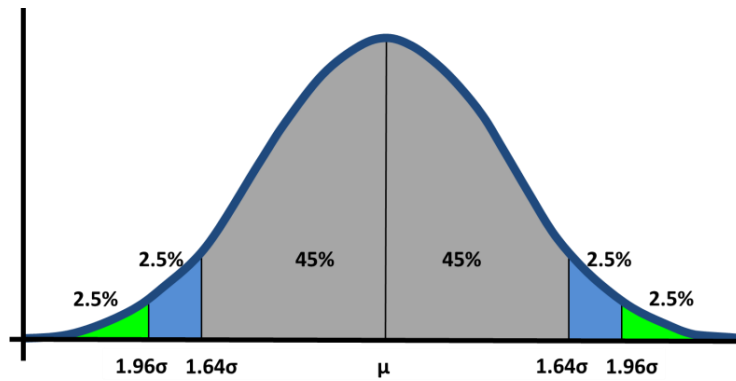
Figure 45 - Normal distribution with its limits as function of the standard deviation

It is important to determine the percentage that can be used as a governing for the weakest sections. During the overtopping simulations most of the damage occurred at the downward side of the slope. After a couple of hours testing with small overtopping wave volumes, multiple bald or weaker spots become apparent. The grass sod is not entirely closed anymore and at some spots the clay layer will be visible. These spots are most susceptible to lead to erosion of the grass sod. When these areas are assumed to be governing for erosion, they can be used to determine the total area of weaker spots. When this is compared to the total tested area during the wave overtopping simulation, it provides insight into the percentage of weaker spots on a slope.

In Figure 46 is an example of this shown (Infram, 2013). If the lowest part of the sod in the figure is observed, about 10 bald spots can be seen in the area up to 5 metres from the toe. This section is 4 metres wide, so the total area between the white lines is 20 square metres. When it is assumed that the damaged sections are approximately the size of 20 by 20 centimetres, a total area of 0.4 square metres is susceptible against erosion of the grass sod. This is approximately 2% of the total area. This corresponds well to the 2.5% limit for a normal distribution. Therefore this value will be applied.

Figure 46 - Example of various bald spots during wave overtopping tests in Millingen aan de Rijn (Infram 2013)

When 1.96 times the standard deviation is subtracted from the mean value, 97.5% of the tested area will have a higher strength than this calculated value. But since the weaker areas will lead to failure, the 2.5% limit is assumed to be governing for the dike section. When this is applied to the sod pulling test locations the governing strength values can be seen in Table 16. The 5% limit is also shown in this table to provide insight in the influence of the chosen limit on the governing critical grass mean normal stress. In Section 8.6.4 the influence of the 5% limit on the critical velocity will be discussed.

Table 16 - Estimated critical stress for weakest sections on a slope

	Calculated critical grass tensile stress [N/cm2]			
	μ	σ	5 % limit	2.5 % limit
Millingen	1,18	0,27	0,74	0,65
Boonweg 1	1,28	0,10	1,12	1,08
Boonweg 2	1,37	0,14	1,14	1,10
Boonweg 3	1,10	0,17	0,82	0,77
Boonweg 4	1,10	0,14	0,87	0,83

8.5.4 Critical velocity of the tested sections

All the parameters have been determined for the relation between the sod pulling tests and the critical velocity formula. It is important to compare the outcome with the results from the wave overtopping simulations. If they lead to the same results, the sod pulling test can be used for the determination of the strength of the grass sod during wave overtopping. In Table 17 the five tested locations are shown, with the corresponding critical grass tensile stress (in N/cm^2). The second half of the table shows the critical velocities (in m/s), where the "calculated" values are based on the sod pulling tests in combination with Equation 39 and the "determined" values are based on the wave overtopping simulator tests. In the calculated values from the sod pulling tests, the relative turbulence intensity is fitted on 0.12, given the 2.5% limit. In the determined values, the critical velocity of the Boonweg 1 and 2 is estimated with the damage criterion for "*no sign of damage*" ($1000 \leq D \leq 7000\ m^2/s^2$).

$$U_c = \alpha_{grass,c}\ r_0^{-1}\sqrt{\frac{(\sigma_{grass,c}(0) - p_w)}{\rho}} = 0.34 * 0.12^{-1}\sqrt{\frac{(\sigma_{grass,c}(0) - 0)}{1000}} \qquad (39)$$

Table 17 - Critical velocity per location estimated from the sod pulling tests (calculated values) and wave overtopping simulator tests (determined values)

	Critical grass tensile stress [N/cm2]			Critical Velocity [m/s]		
Location	μ	σ	2.5 % limit	Calculated	Determined	Difference
Millingen	1,18	0,27	0,65	7,23	7	3%
Boonweg 1	1,28	0,10	1,08	9,33	8 - 9.5	2 - 16%
Boonweg 2	1,37	0,14	1,10	9,38	8 - 9.5	1 - 17%
Boonweg 3	1,10	0,17	0,77	7,85	8	-2%
Boonweg 4	1,10	0,14	0,83	8,14	8	2%

It can be seen from the table that there is a strong correlation between both values of the critical velocity for Millingen and the Boonweg 3 and 4. Especially when the calculated results are rounded towards whole or half numbers, which is done for the determined critical velocities.

For Boonweg 1 and 2 it is a bit harder to determine the correlation, since there is a band of estimations for the critical velocity from the wave overtopping simulator tests. The calculated values for the critical velocity are well inside the given range. However, when the damage criterion of 1000 m^2/s^2 is used, both methods give approximately the same results. This leads to the assumption that Boonweg 1 and 2 are stronger than expected based on the wave overtopping simulations, where they were thought to have approximately the same strength as Boonweg 3 and 4. On the other hand, if the critical velocity of the Boonweg 1 and 2 is indeed only a bit higher than 8 m/s, the sod pulling tests can still give a decent approximation of the strength for these locations.

8.6 Restrictions and vulnerabilities

The previous section shows that there is a good correlation between the determined critical velocity from the wave overtopping simulations and the calculated critical velocity from the sod pulling tests. This means that the sod pulling test is a decent and quick method for determining the strength of a grass sod during wave overtopping. However, a few remarks have to be made regarding this relation. First the sod pulling test will be discussed, after which the critical velocity formula and the Cumulative Overload Method will be handled. This section will end with a sensitivity analysis of the most important parameters.

8.6.1 Sod pulling test

In order to link the sod pulling test with the critical velocity formula, the critical grass mean normal stress has to be determined. This is done in the practical way, including a shape factor developed in this thesis. The previously developed theoretical method results in less constant values, but these values are on average a factor 1.5 higher. It is assumed that the values from the practical method are a better representation of the reality, since more influences are taken into account. However, there are still some uncertainties in the critical grass normal stress, partly due to the size of the shape factor. This factor corresponds linear towards the critical grass mean normal stress, therefore a small adjustment in the shape factor results in a different stress. Since the shape factor is based on a general estimation of the area of the cut corners, it could be a slightly different value in reality. However, it is expected that the practical method still gives more accurate results than the theoretical method, which is based on the general exponential decrease of roots over the depth.

Another point of interest is to determine the required quantity and locations of the sod pulling tests for a decent overview of the dike section. For the calculation of the critical velocity an average and standard deviation for the critical normal stress has to be established per dike section. So enough tests need to be carried out in order to find the right distribution parameters. During this thesis about 20 tests are performed per location, which resulted in an acceptable indication of the strength of the sod. However, for a better approximation for the parameters of the normal distribution it is recommended to do at least 30 tests per location. This will reduce the inaccuracy of the average and the standard deviation. With the parameters of the normal distribution, the 2.5% value can be determined. This percentage is estimated from the damaged area on a slope as a function of the total area. It is a rough estimation, so there is some uncertainty in how representative this 2.5% value is.

The sod pulling tests are carried out in close proximity of one another, at the bottom half of the slope. The tested locations are chosen at random, so visually stronger and weaker sections are both tested for their strength. It could be interesting to test only the visible weaker sections of the slope, but this also has a disadvantage since the coverage and herbs are not perfect indicators for the measured strength. During the tests it was noticed that visually weaker areas provided more resistance than expected beforehand. The same is possible for visually strong sections, which could result in a low measured value. Therefore is not preferred to test only the visibly weaker sections, so it is recommended that the tested sections are selected at random.

The assumed normal distribution also has a disadvantage. It can result in negative values for the strength of a sod for certain distribution parameters, which is not physically possible. A lognormal distribution has only positive values and has a larger tail on the stronger side of the average. This is however less in line with the measured distribution in Appendix E1. The normal distribution is applied in this thesis for locations with at least a factor 4 difference in average and standard deviation, so this cannot result in a negative strength of the critical grass mean normal stress.

Furthermore it is advisable to perform the tests only at the lower half of the slope because of the higher damage risk during wave overtopping due to the higher occurring velocities.

Lastly, the way of testing the sod is important for the results. In this thesis three different frame sizes are tested. The 10 by 10 centimetres frame size was too small to generate reliable results. Therefore this frame should not be used for further testing. The 15 by 15 centimetres and the 20 by 20 centimetres frame size gave approximately the same critical mean grass normal stress. One frame size did not generate less constant results compared to the other, therefore both can be used in further testing. However, since the shape factor is an approximation of the total area, the influence of this factor decreases with an increasing frame size. This has been taken into account with the size of the factor, but the larger the frame size, the better the representation of reality. Because of this the 20 by 20 centimetres frame size is recommended for testing.

Besides the different frame sizes, two different test conditions (2 and 4 sides cut) are performed in this thesis. The condition 2 test measures the strength of the bottom and two sides, where the condition 4 test only measures the strength of the bottom roots. For the strength during wave overtopping the strength of the intact sod needs to be known, which can be calculated by the practical approach with the coupling of the condition 2 and 4 tests. However, Section 6.4 shows that there is a factor of 1.56 difference between the condition 2 test and the strength of an intact sod. Since this factor is almost constant over all the tests, this could be used to convert the measured value for condition 2 test towards an intact sod.

Almost all tests in this thesis are performed under saturated conditions, since these mimic most of the soil conditions during wave overtopping. There are some tests carried out for unsaturated conditions, which resulted in higher measured strength of the grass. This was expected beforehand because of the suction pressures in the soil. However, this influence is not constant per day and location since it depends on the weather conditions over the last few weeks. In order to remove this influence, the tests should be performed under fully saturated conditions.

In short, it is recommended to perform at least 30 tests at random locations in order to establish the parameters for the normal distribution and find the 2.5% tail value. These tests should be performed as condition 2 test with the 20 by 20 centimetres frame size and under fully saturated conditions.

8.6.2   Critical velocity formula

Some uncertainties in the sod pulling test and resulting critical grass mean normal stress are mentioned. However it is also important to discuss the other parameters in the critical velocity formula. One of the main points of discussion in the equation is the usage of the Shields parameter. This parameter is based on the transport of loosely packed sand on a river bed. Emmerling (1973) later investigated the influence of normal and shear stress on particles. Both methods give as an estimation 0.03 as value of the Shields parameter. However, erosion of a grass sod is not comparable in behaviour with loose sand. So it is not clear how this should relate in the parameter. In this thesis the value of 0.03 is applied, but not as an independent Shields parameter. The value of 0.03 is put into the already existing alpha factor, excluding the Shields parameter in its current form from the equation. In doing so the influence of this factor is constant and the theory of Shields is not directly associated anymore with the erosion of grass.

Another important parameter in the equation is the relative turbulence intensity. This factor has major influence on the outcome, since it reacts proportional to the critical velocity. It is already a small factor, so when it is adjusted by one hundredths, it already changes the value of the critical velocity with approximately 8%. A second disadvantage of the turbulence intensity is that it is a not fully understood parameter. It is an important parameter in turbulent flow, but it is hard to determine the exact value and its exact influence on the erosion. This leads to a range of relative turbulence intensities which could be used for overtopping waves, but is impossible to determine exactly. Combined with the influence of this parameter on the final outcome, further research has to be done towards the relative turbulence intensity to investigate this problem.

The pore water pressure is still present in the critical velocity formula as an input parameter. During the tests in this thesis, the ground was artificially watered for two hours after which testing began. It

is assumed that the pore water pressure is reduced to zero because of this, but this is not measured. The pulled out sods were wet or soaked and therefore the resulting suction pressures should be small. However, if small suction pressures are applied to the equation, the critical grass mean normal stress reduces in value when it becomes completely saturated. This results in a lower critical velocity of the grass layer and thus in overestimation of the strength. But since the sod was artificially watered for two hours it is assumed that all the suction pressures are gone during the sod pulling tests.

8.6.3 Cumulative Overload Method

The last point of discussion is the damage factor in the cumulative overload method for no sign of damage. In an ideal situation this damage factor is not necessary because all slopes will be tested until signs of failure occur. However, since the wave overtopping simulation has a limited volume some sections do not get big enough loads to start the erosion process.

In order to tackle this problem an assumption is made for the case of no sign of damage. This damage factor should at least be lower than 7000, but an estimation of <1000 m^2/s^2 is also possible. Therefore this damage factor is set as both these values. This leads to two values between which the critical velocity should be. However, there is quite some difference between both values, so it is difficult to say how good the calculated value with the sod pulling tests matches the results from the wave overtopping simulator. Based on the other three locations, the sod pulling test results from Boonweg 1 and 2 should also give a decent approximation of the critical velocity. This would mean that these two sections are stronger than expected during the overtopping simulations. It would be interesting to check with the wave overtopping simulator whether the critical velocity of the Boonweg 1 and 2 is near 8 or 9.5 metre per second. When this is done, it is possible to determine the damage criterion for no sign of damage more accurately.

8.6.4 Sensitivity analysis

In this paragraph a sensitivity analysis is carried out in order to check the most uncertain parameters in the critical velocity formula. There are four parameters which have been determined with relative certainty, but it is important to check what happens to the critical velocity if the values change slightly. The four parameters have their own relative uncertainty, so they all have an estimated value and possibly a deviation from that value. These values are provided in Table 18.

- The shape factor for both the 20x20 cm and 15x15 cm frame sizes are given and used to determine the sensitivity. It is interesting to check what happens with the critical velocity if this factor changes slightly.
- For the tail of the normal distribution the 2.5% value is assumed as governing for the strength of the dike section. The sensitivity on the critical velocity of this parameter is based on the difference when a 5% tail value is assumed.
- The relative turbulence is set at 0.12 at the bottom half of the slope, but it can be somewhere between 0.10 and 0.15. To investigate the influence on the critical velocity the relative turbulence is altered from 0.12 to a value close to it.
- The pore water pressure is set to zero in the calculation, because the sod is watered before testing. But it is possible that there were still some small suction pressures (order 0 to 3 kN/m^2) in the sod. Therefore it is important to check this influence on the critical velocity.

Table 18 - Possible deviation in parameters of critical velocity formula

Parameter	Value	Deviation
Shape factor	1,10 & 1,15	0,05
Tail of distribution	2,50%	2,50%
Relative turbulence intensity	0,12	0,01
Pore water pressure [N/cm2]	0	0,1

In Table 19 the sensitivity of the parameters is shown. The values are provided for every location and as an average over all locations. The percentage shown is the difference in critical velocity when the value of the parameter is changed by one deviation. The higher the percentage the more the critical velocity is influenced by a small adjustment in the parameter. The relative turbulence intensity is the most important parameter, since it has a large influence on the critical velocity. It is also the most uncertain parameter. Therefore the assumed value could deviate significantly in reality. The turbulence is constant for all locations, since it does not change with the strength of the grass sod in the equation.

The other parameters change with the strength of the sod, which shows that the sensitivity is different per location. The influence of the pore water pressure is larger on the critical velocity compared to the shape factor and the tail size of the normal distribution. Small suction pressures could still be present during the sod pulling tests, which result in an overestimation of the strength of the grass sod. This will lead to a lower critical velocity than calculated under the assumption of a fully saturated sod.

The influence of the shape factor and the 2.5% tail of the distribution on the critical velocity is relatively small. The assumed deviation from the used value is large compared to the turbulence and water pressure, but the influence of it on the critical velocity is negligible. In other words, additional research should focus on the size of the relative turbulence during overtopping waves and on the influence of possible existing suction pressures in the sod, even after artificially watering for two hours.

Table 19 - Sensitivity analyses of critical velocity formula

Location	Shape factor	Tail size	r_0	p_w
Millingen	2%	6%	8%	8%
Boonweg 1	3%	1%	8%	5%
Boonweg 2	3%	2%	8%	5%
Boonweg 3	3%	3%	8%	7%
Boonweg 4	2%	3%	8%	6%
Averaged	2%	3%	8%	6%

8.7   Systematic approach from sod pulling tests to critical velocity

The relation between the sod pulling test results and the critical velocity is known. So it is good to visualize the different steps. This is presented in Figure 47, where the first step is performing the sod pulling test and the end result is the critical velocity for that tested section. In Figure 47 the blue oval areas represent the results of the different steps. The grey rectangles represent the parameters which influence the outcome, whereas the white rectangles are used to determine these parameters.
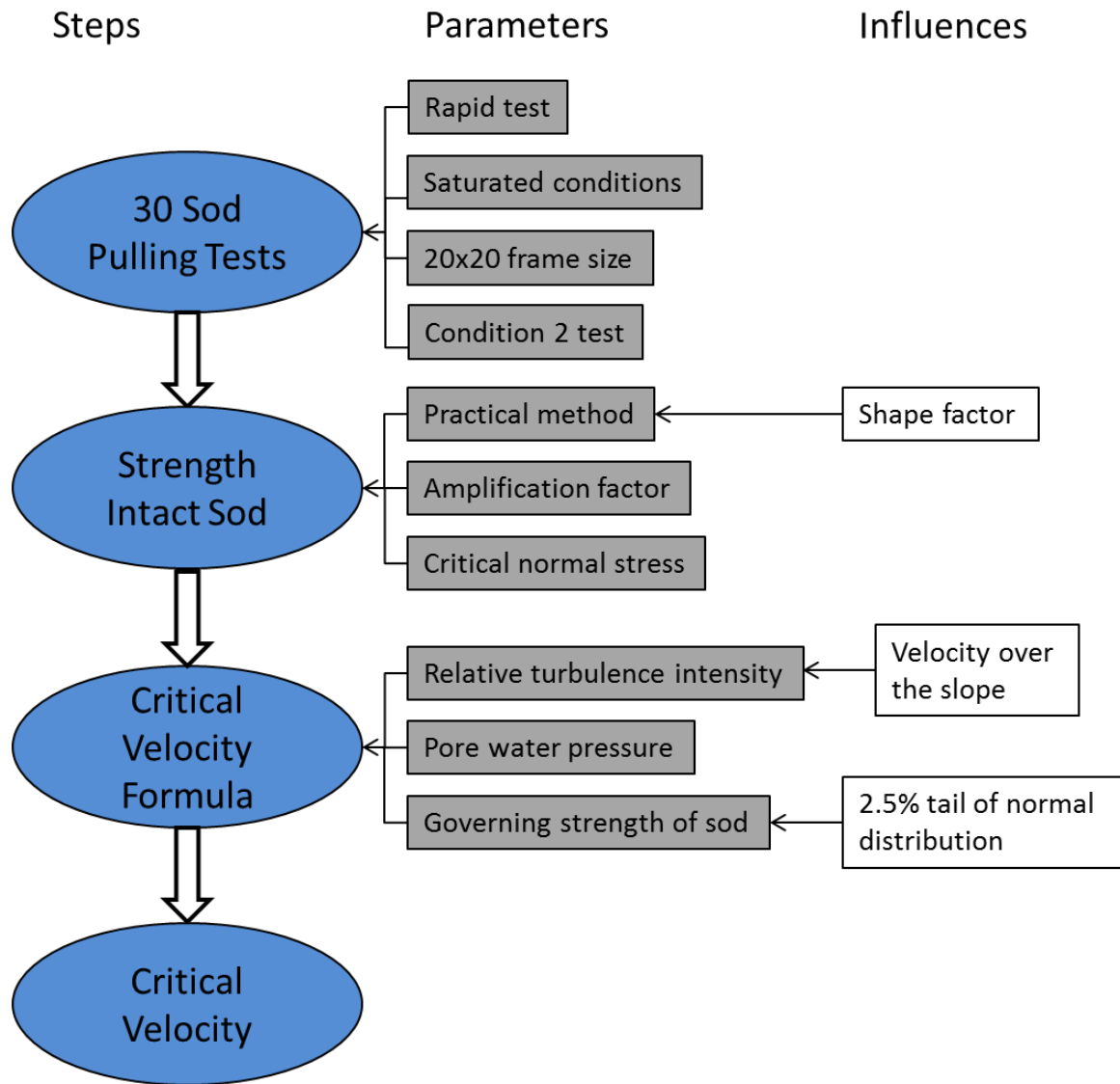
Figure 47 - Systematic plan from sod pulling tests to critical velocity

PART IV -

CONCLUSIONS & RECOMMENDATIONS

9   Conclusions

The final part of this thesis contains the conclusions and recommendations which follow from the research. Suggestions for future research are formulated in the recommendations in Chapter 10. In this chapter a summary of the most important conclusions from the main report will be given. For a more elaborate version of the conclusions, see the Executive Summary at the start of this report.

1. *The current and old methods for determining the grass sod quality have limitations when looking for the strength of sod during wave overtopping conditions.*

2. *The sod pulling method is a practical way of determining the strength of the grass sod, where the data from all the individual sod pulling tests from one location are to be combined into an average value and standard deviation for the strength of the tested dike section.*

3. *The practical approach for determining the strength of an intact grass sod provides more reliable results compared to the theoretical approach by Hoffmans. In the practical approach a small shape factor α (1.10 to 1.20 depending on the frame size) is introduced to compensate for the cutting of the sides and corners during the testing. The practical approach uses these two equations.*

$$\sigma_{grass,c} = \frac{F_i}{A_b + 4 * A_s} \qquad with \qquad F_i = \alpha * [F_2 + (F_2 - F_4)]$$

4. *The 20 by 20 centimetre frame size should be used for testing to give the most reliable results. It is possible to calculate the strength of an intact sod directly from the measured value of the condition 2 test, by multiplying the measured force with an amplification factor of 1.56.*

5. *A grass sod is influenced by fatigue. After the sod has reached a certain vertical displacement, some roots will break leading to a weaker sod after the external force is removed. It requires a smaller force to reach the same elevation from that moment on.*

6. *A normal distribution can be assumed for the strength of the grass sod per location. The 2.5% tail on the weaker side of this distribution is assumed as representative for the strength of dike section.*

7. *To determine parameters of the normal distribution for the strength of a dike section, at least 30 sod pulling tests need to be performed. These tests need to be performed as rapid condition 2 test with the 20 by 20 centimetres frame size under fully saturated conditions. The location of each test needs to be selected at random at the bottom half of the slope.*

8. *A new damage factor for the Cumulative Overload Method is introduced:*
   No sign of damage $\qquad \sum(U^2 - U_c^2) = 1000 \leq D \leq 7000 \ m^2/s^2$

9. *The equation for the critical velocity (U_c) derived by Hoffmans et al. in 2008 can be used to link the sod pulling tests with the critical velocity, through the critical grass mean normal stress ($\sigma_{grass,c}$). In this relation is the relative turbulence fitted on 0.12, given the 2.5% value for the weakest spots.*

$$U_c = \alpha_{grass,c} \ r_0^{-1} \sqrt{\frac{(\sigma_{grass,c}(0) - p_w)}{\rho}}$$

9.1 Answer research question

The main research question in this thesis is:

"Can the results from the sod pulling test be used to determine the critical velocity of grassed slopes on dikes in the Netherlands during wave overtopping conditions?"

The answer to this question can be summarized into:

The sod pulling test can be used as a predictor for the strength of the grass sod. It provides results that are reliable enough to determine the critical velocity of a dike section. The forces measured during the tests need to be rewritten into critical grass normal stress ($\sigma_{grass,c}$), which is one of the input parameters in the equation below for determining the critical velocity of the grass sod. The other parameters included in the formula are the relative turbulence intensity (r_0), pore water pressure (p_w) and the density of the water (ρ).

$$U_c = \alpha_{grass,c}\ r_0^{-1} \sqrt{\frac{(\sigma_{grass,c}(0) - p_w)}{\rho}}$$

Table 20 gives the critical grass mean normal stresses determined with the sod pulling tests and the critical velocities of the tested dike sections. The "calculated" values are the outcomes from the sod pulling tests in combination with the critical velocity formula. The "determined" values have been defined during the wave overtopping simulations. . There is a strong correlation between both values for the critical velocity at the tested locations, especially when the "no sign of damage" criterion of 1000 m²/s² is used. This leads to the assumption that Boonweg 1 and 2 are stronger than expected based on the wave overtopping simulations, where they were thought to have approximately the same strength as Boonweg 3 and 4. On the other hand, if the critical velocity of the Boonweg 1 and 2 is indeed only a bit higher than 8 m/s (if D = 7000 m²/s²), the sod pulling tests still give a decent approximation of the strength for these locations.

Table 20 - Critical velocity per location estimated from the sod pulling tests (calculated values) and wave overtopping simulator tests (determined values)

	Critical grass tensile stress [N/cm2]			Critical Velocity [m/s]		
Location	μ	σ	2.5 % limit	Calculated	Determined	Difference
Millingen	1,18	0,27	0,65	7,23	7	3%
Boonweg 1	1,28	0,10	1,08	9,33	8 - 9.5	2 - 16%
Boonweg 2	1,37	0,14	1,10	9,38	8 - 9.5	1 - 17%
Boonweg 3	1,10	0,17	0,77	7,85	8	-2%
Boonweg 4	1,10	0,14	0,83	8,14	8	2%

10   Recommendations

Most of the recommendations follow directly from the conclusions and need only little further explanation. The recommendations can be divided into three sections, of which the first is about the relation between the sod pulling test and the critical velocity formula. The second section of recommendations can be related to the sod pulling test, while the last recommendations concern the grass strength and the influence of the maintenance on the strength.

1. ***Recommendations to improve the relation between the sod pulling tests and the critical velocity***

- *Validate the established relation between the sod pulling test and the critical velocity formula.*

This validation should preferable be done when new wave overtopping simulator tests are planned. Before the simulations begin, sod pulling tests could be performed on the same dike section. The results from the sod pulling test can be used to give an estimation of the critical velocity of the slope. Afterwards, wave overtopping simulations can start a few metres away from the sod pulling tests, so that the critical velocity can also be determined based on these simulations. The results from both methods should than be compared in order to validate the relation.

If there are no wave overtopping simulations planned in the near future, it is possible to validate the relation by performing sod pulling tests at locations where wave overtopping simulations have been executed in the past.

- *Perform additional research to gather knowledge in the relative turbulence intensity along the slope.*

The relative turbulence intensity is a relatively unknown parameter. It is difficult to measure or determine this parameter, but it has great influence on the calculated critical velocity with the sod pulling tests. So it is recommended to gather more knowledge concerning the relative turbulence intensity.

- *Investigate the accuracy of the damage factor for "no sign of damage" in the Cumulative Overload Method.*

At the locations Boonweg 1 and 2 no damage occurred during the wave overtopping simulations, therefore a new criterion in the Cumulative Overload Method is introduced. The damage factor for "no sign of damage" does require further research into the assumed value. This damage factor should at least be lower than 7000, but an estimation of <1000 m^2/s^2 could also be valid. In this thesis the critical velocity of Boonweg 1 and 2 is calculated for both values, but there is quite some difference between the outcomes. It would be interesting to test the Boonweg 1 and 2 again with the overtopping simulator, but this time continue the tests until the slope fails. If this test results in one of the calculated critical velocities, the factor for "no sign of damage" can be estimated.

- *Validate the relation between the sod pulling tests and critical velocity near obstacles and transitions.*

In this thesis obstacles and transitions on the slope are neglected. However, they are part of the Cumulative Overload Method in the form of a load (α_M) and a strength factor (α_S). It requires further research to study these parameters and their influence on the strength of grass sod and on the critical velocity near these obstacles and transitions.

- *Investigate the relation between the strength of the grass sod and the loads during wave run-up and wave impact.*

Wave overtopping is the wave load which is used in this research in relation to the grass strength. But an incoming wave has three distinct loads on a dike, of which wave overtopping is the last to happen in time. It is interesting to find a relation between the strength of the grass and the wave run-up, which is comparable in behaviour to wave overtopping. Wave impact loads are not comparable to wave overtopping loads, so additional research into the relation between the strength of grass and impact loads can complete the circle of the relation between the strength of a dike and the loads of an incoming wave.

2. *Recommendations related to the sod pulling test*

- *Check whether the determined strength of an intact sod with the practical method is a good representation of reality.*

In this research two different methods of determining the strength of an intact grass sod have been used. However, there is a factor 1.6 difference in the outcome between both methods. The practical method is expected to be more accurate, because it provides more constant results over the different testing methods. But it is important to check whether the practical method results in the right values. This could for example be done with a testing device, where no sides are cut before testing. When pins are inserted into the grass sod from above the sod (like a claw) the strength of an intact sod can be tested. Another option is to construct a pull frame with the dimensions of 15 by 30 centimetres. This way the total tested area becomes twice as large as the 15 by 15 frame size. The ratio between the measured forces between these frame sizes can be used to determine the size of the shape factor.

- *Investigate a method to determine the strength of the grass sod under saturated conditions for tests performed under different degrees of saturation.*

The sod pulling device is a simple design with as final goal to let dike managers determine the strength of the dike sections. However, in order to determine the strength of grass under saturated conditions, the ground has to be artificially watered for two hours before testing can begin. This watering requires a lot of extra equipment, like a generator and pumping installation. This is not preferable since the sod pulling device was developed to be a simple method of testing. Further research into saturation could result in a factor to decrease the measured strength of the sod as a function of the degree of saturation.

3. *Recommendations for further research into the strength of grass*

- *Investigate the influence of fatigue of a grass sod on the strength during wave overtopping.*

Fatigue of the grass sod can have large influence on the measured strength during testing. The more load repetitions, the weaker the grass sod will become. The fatigue tests performed in this research provided some insight into the behaviour, but additional research is required to determine the exact influence of fatigue. The new fatigue tests should be performed with a constant imposed force instead of an imposed elevation in order to obtain more useable results.

Furthermore, the modulus of elasticity of a grass sod is now determined, therefore it can be compared to another wood like product with the same modulus. This can provide more insight into the behaviour of the grass sod under fatigue.

- *Investigate the differences between the determined strength of dike sections and the expected strength based on the maintenance type.*

The previously used theoretical method of determining the strength of a grass sod based on the maintenance type is not in accordance with the determined strength with the sod pulling tests and overtopping simulations. It is important to investigate why this difference exists and what this means for the strength of the different types of maintenance. If there is one specific type of maintenance leading to the strongest grass sod, it can become the prescribed maintenance method for dikes in the Netherlands. Extra sod pulling tests at different locations and maintenance types are recommended to investigate this further.

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APPENDICES

A   Location sod pulling tests

Sod pulling tests are performed on two locations in the Netherlands, at the Boonweg near Sint Jacobiparochie (Friesland) and near Millingen aan de Rijn. Both locations are shown in the map of the Netherlands (see Figure 48) and more detailed in Figure 49 for Boonweg and Figure 50 for Millingen aan de Rijn

Figure 48 - Locations of testing in the Netherlands (maps.google.nl)

A1   Boonweg 1 to 4

The tested sections near St Jacobiparochie are shown in the figure below. All tests are performed in the middle of the test sections at a distance from 2 till 9 metres from the toe. Boonweg 1 is the regular maintenance of the sea dikes in Friesland, which is tested from 5 to 10 metres next to test section 2.
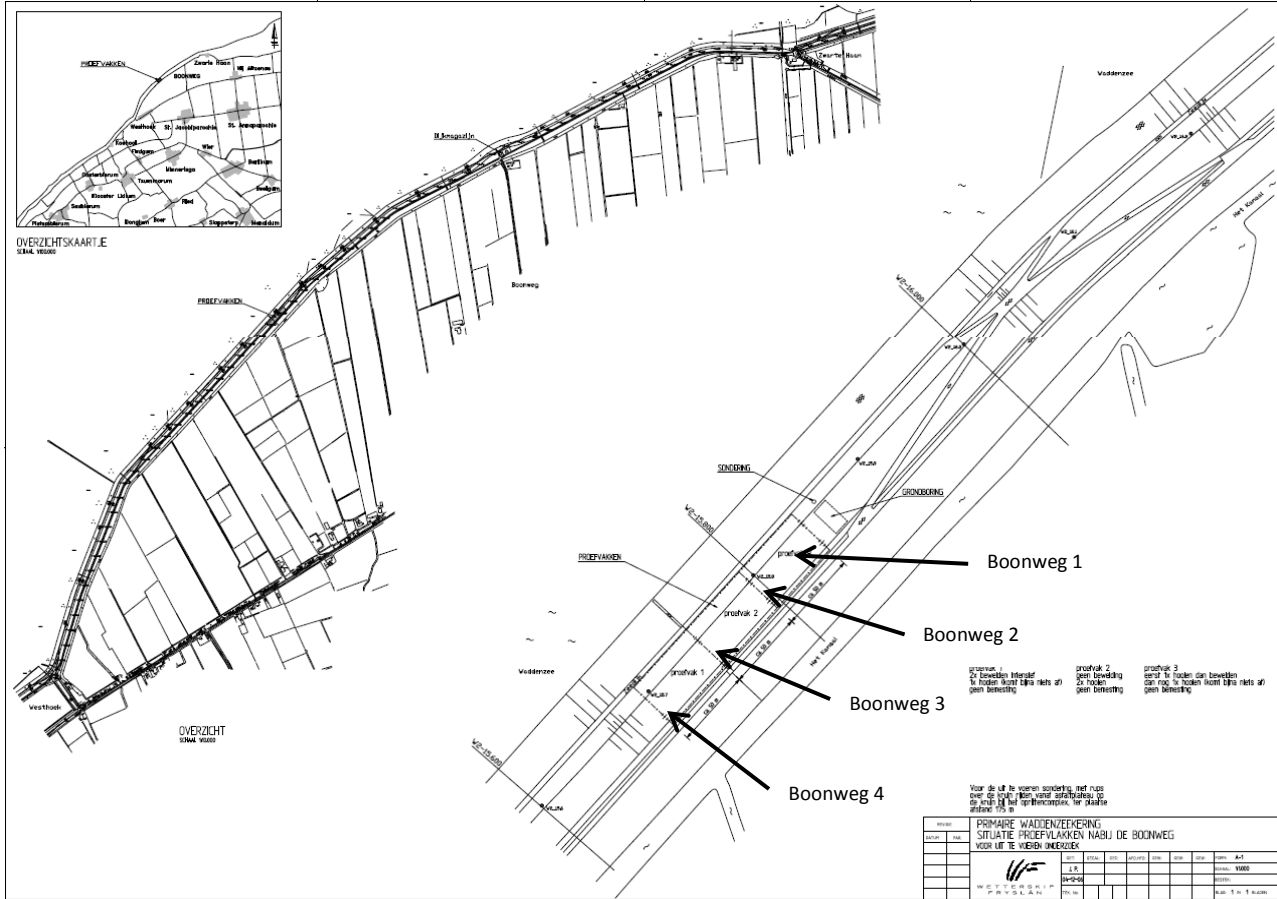

Figure 49 - Location of the tests at the Boonweg sections 1 to 4

A2   Millingen aan de Rijn

The tested section near Millingen aan de Rijn is shown in the figure below. The North side of the dike is tested between dike pole 023 and 024, with a distance of 23 and 29 metres from pole 024.

Figure 50 - Location of the tests near Millingen aan de Rijn (maps.google.nl)

B   Measured data

In this appendix information is given about the tests performed in Millingen aan de Rijn and Boonweg 1-4. First the difference in measurements between the tension gauge and the Deltares equipment is explained. After that, graphs are made to show what can be done with the force and displacement data stored on the logger.

B1   Difference in measurements

During the tests, two types of equipment were used to measure the tensile force. The first one was a tension gauge, which had to be read manually and was accurate up to whole kilogram forces. These values are multiplied by gravitational acceleration, therefore is limited up to 10 Newton. The second type of equipment is a force and displacement sensor from Deltares. This device measures the force and displacement 4 times every second. This is accurate up to 0.5 Newton. This means there is also a difference in accuracy of the two devices.

With the tension gauge only the maximum occurring force can be measured, where the other device registers the whole test. To test if this gives the same (maximum force) results, a comparison between the two is made. If this is the case it depends on the desired data which device should be used in further tests. The difference has been determined at the maximum measured values with both methods. This difference is plotted as a value (Figure 51a) and as a percentage (Figure 51b) of the maximum value.
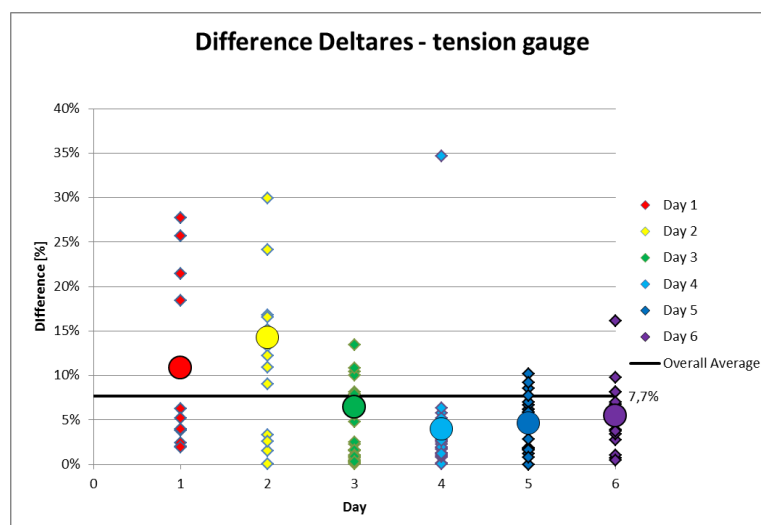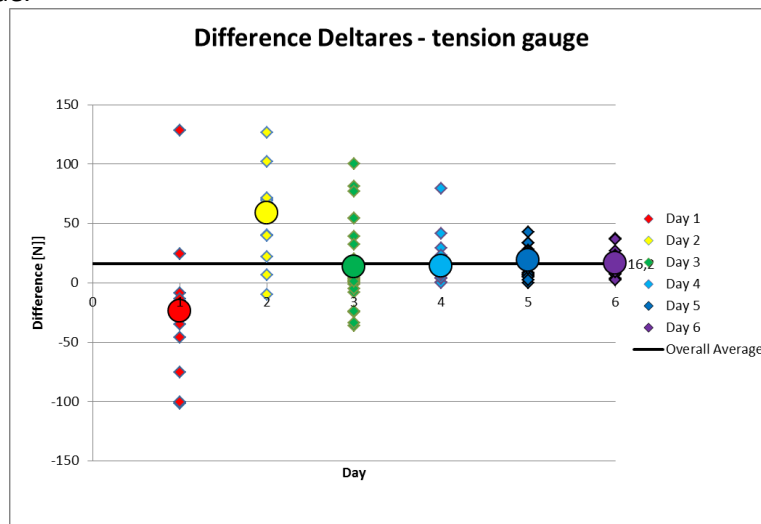

Figure 51 a,b - (Relative) Difference in measurements between Deltares equipment and tension gauge

Conclusions

From the figures it can be concluded that the average difference between the two measurement devices are in the order of 16 N. This is about 8% of the measured force. Furthermore the results are scattered around +100 and -50 Newton difference. This difference is however mostly the case during the first 4 days. This can be explained by improper use of the tension gauge. It was recalibrated a few times a day, when a force was shown which didn't agree with the starting point of measurement. The last 2 days the tension gauge was set to zero when only the pull frame was attached, which results in more correct measurements. The average difference between the two devices is still about 16 Newton, but it is a more constant difference. This can partly be explained by the fact that the tension gauge is read in kilogram force, without any decimals. This is on average 5 Newton, which declines the gap further.

The 16 Newton is also on average 5% of the maximum force, so the influence of this difference is not that large.

Discussion

The results from the last two days show that the tension gauge can also be used as a force measurement device, but it is only possible to measure the maximum force. The change of the force (and displacement) in time is not possible to measure with the gauger. Later on in this research will be investigated if the maximum force is the only parameter needed or that the change of the force (or displacement) is used for calculating the strength of a grass sod during wave overtopping.

B2   Overview available data

Here an overview is given of what can be done with the gathered data. With the tension gauge only the maximum force can be measured, but when using the Deltares equipment, graphs can be made showing the measured parameters. Some of the representative graphs are shown in this appendix.

There are four graphs shown, consisting of 5 different tests per graph. Each graph is representative for a given test method. Tests are performed with two types of frame sizes and two different testing methods (condition 2 & 4), which results in groupings of four graphs. This is done for all the locations tested during this thesis, but since this is only used as indication of what the data looks like, only the results from Boonweg 1 are shown. Furthermore, there are three different types of diagrams: The first type is a force time graph, the second type is a displacement time graph and the last type is a force displacement graph.

B2.1   Force time diagrams

The first type of graph is the force time diagram (see Figure 52 a-d). This shows the development of the force during the imposed increasing elevation. The maximum strength of a particular test can be determined from this graph. A wider peak means that the sod had a higher resistance at different levels of elevation. So when the maximum value is reached for a small amount of time, there is still a relative high strength left in the sod. When a small peak is visible in the graph, the remaining strength after the maximum load is small. A smaller force can rip out the sod completely after the first large load.
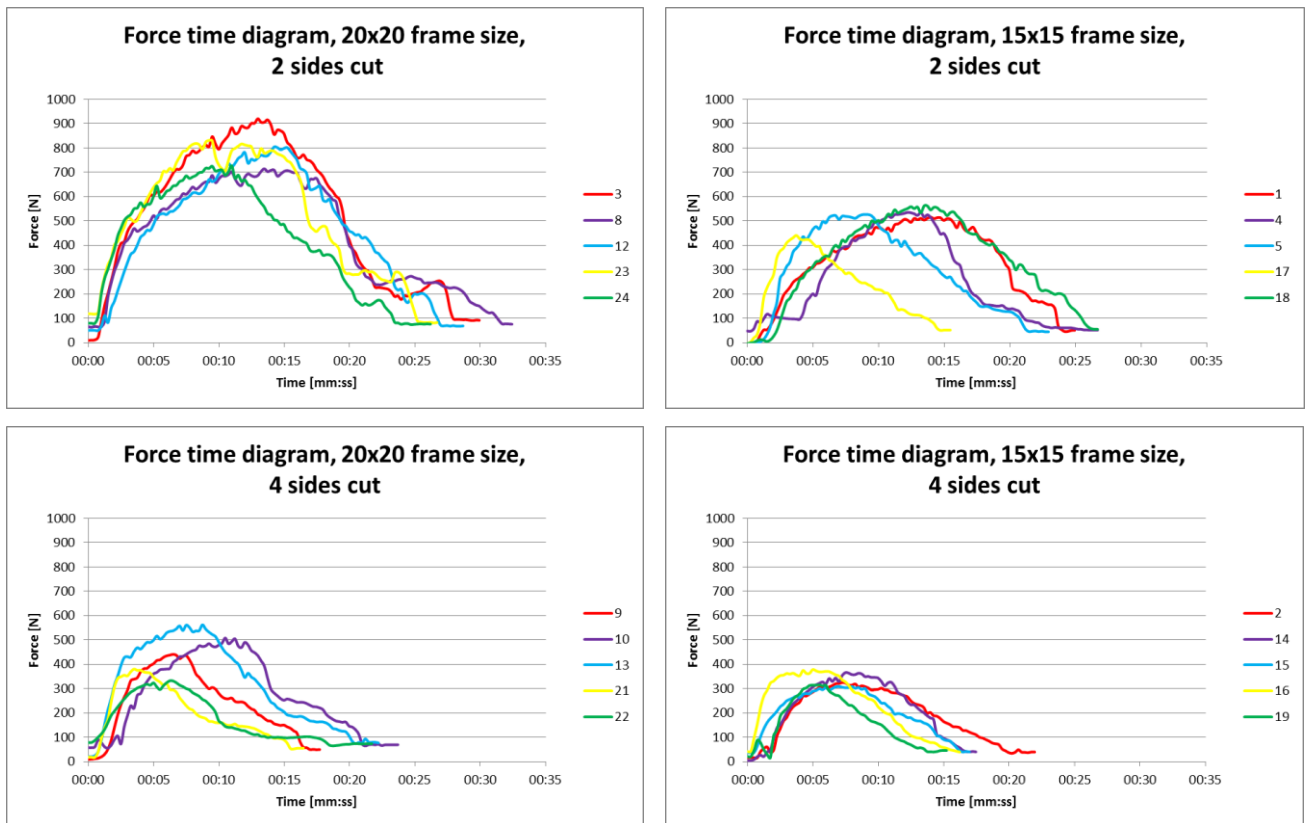
Figure 52 a,b,c,d - Examples of force time diagrams from the Boonweg 1

The graphs of the force as function of the time are similar in shape, but some tested sections are stronger than others, even for areas close to each other. This is due to the heterogeneity of grass, which leads to higher or lower peaks in the data. Also the size of the frame and the number of sides cut loose are important parameters for the force needed to pull out the grass sod. A bigger frame size (20 by 20 cm) results in higher forces than the 15 by 15 frame size. Furthermore, the graphs show that the condition 2 test results in higher forces than the tests with all sides cut. These conclusions are expected according to the theory. When using a larger frame size, a larger area of the sod is pulled upwards. In larger areas are more roots present, which result in higher forces. The same is true for the condition 2 test. The sides provide extra resistance against the uplifting motion. The exact influence will be investigated in the main report.

B2.2 Displacement time diagram

The second type of graph is the displacement time diagram (see Figure 53 a-d). This graph shows the increase of the imposed elevation in time. A linear increasing line corresponds to a constant elevation of the grass sod. The elevation speed was kept as constant as possible with the rotary wheel during all tests performed in this thesis. When the grass sod had failed, the rate of elevation was increased in order to remove it from the frame.

From the graphs follows that the grass sods are pulled upwards with a speed of 3 to 4 millimetres per second. There is some variation in this speed, due to the way of testing. A rotary wheel is rotated by hand in order to lift up the sod. At the moment the sod reaches it maximum resistance, it requires more effort to rotate the wheel. Because of this, it is hard to keep the rotating speed constant. It is not possible to have a more constant elevation without changing to a different method than the rotating wheel.

It is however not that important to keep the elevation speed exactly the same during the different tests. The measured forces with the corresponding elevation are not influenced by this speed, unless this rate of elevation is so high that the roots have not enough time to respond to the elevation. This
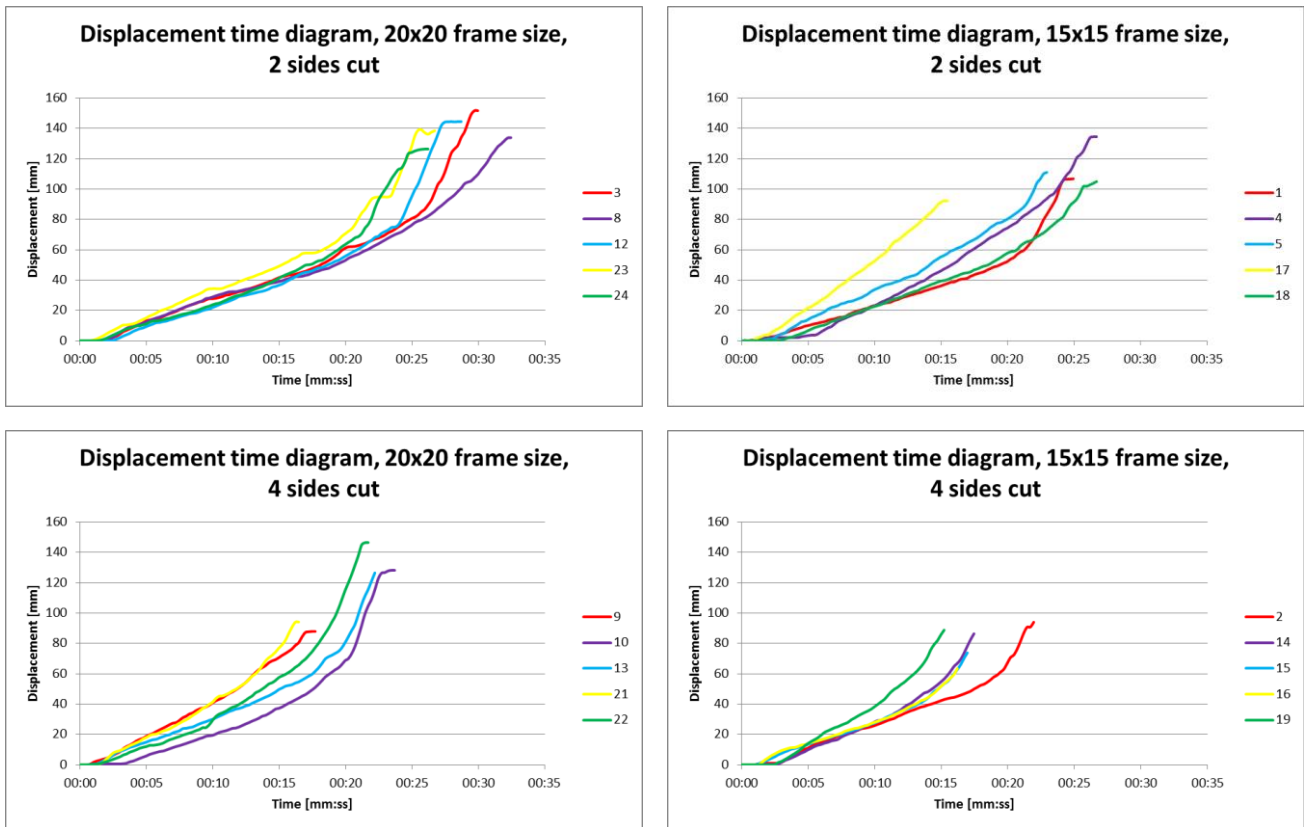
Figure 53 a,b,c,d - Examples of displacement time diagrams from Boonweg 1

phenomenon does not occur in this case with 4 millimetres per second, therefore there is no reason to change to a different handling system.

A disadvantage of the Deltares displacement measurements is that there is no real starting point during the tests. During the setting up of the test, when the equipment is connected to the sod, the frame undergoes a small initial movement. This is in the order of a few millimetres. In the gathered data there needs to be a starting point for which the displacement (and time) is set to zero. The rest of the points are calculated in accordance with this point. Due to this, the starting value of the displacement is set to zero, but could already be a couple of millimetres in the real test. This influence is hard to eliminate from the results, because it is not constant over all the tests. With an adjustment in the test set-up this influence can become smaller, but it results in extra handling and is time consuming. So since the influence is not that big, this adjustment is not preferred.

B2.3   Force displacement diagram

The third type of graph shows the force as a function of the displacement (see Figure 54 a-d). These graphs show the relation between the increasing displacement and the resulting force. It is possible to determine the displacement at which the maximum force occurs. This is an important parameter, because after this maximum force or displacement is reached, the sod has lost most of its strength and will fail under smaller loads. The width of the peak is again an indication for the remaining strength of the sod after imposing a certain elevation and releasing it.

The force displacement graphs show a similar shape, where there is a peak in the maximum force around 20 to 40 millimetres elevation. There is some difference per frame size and number of sides cut. The exact relation will be dealt with in the main report of this thesis.
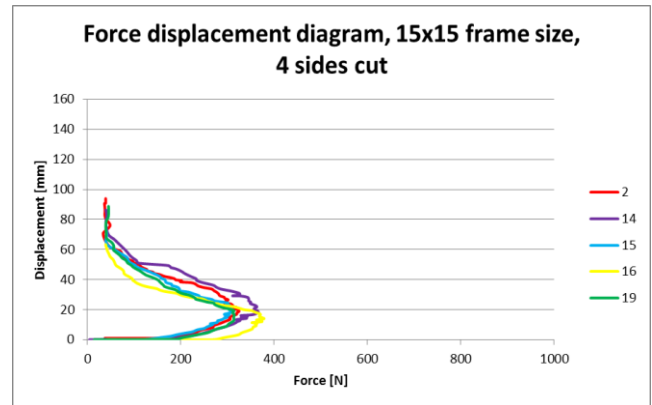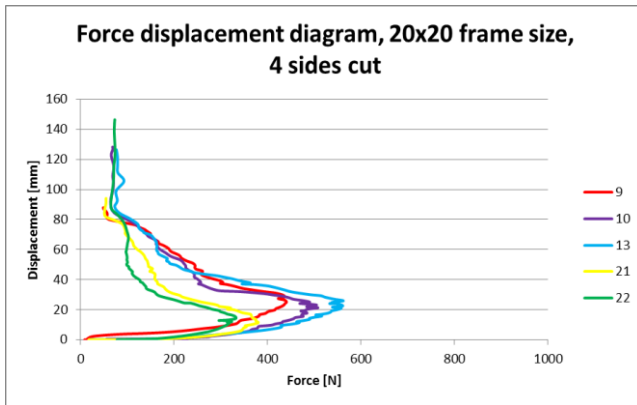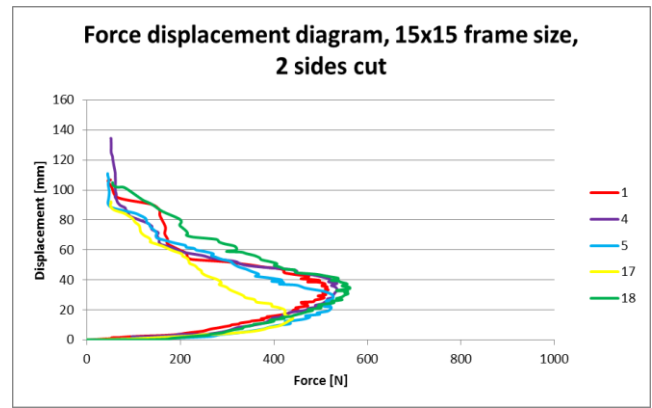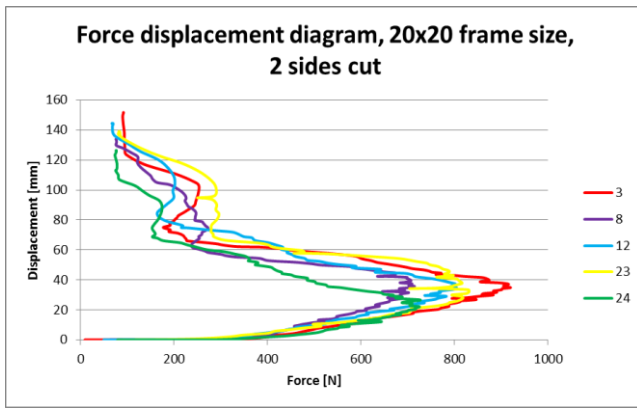
Figure 54 a,b,c,d - Examples of force displacement diagrams

C   Data analyses

In this Appendix some small data analyses are performed, which could be important to the behaviour of the grass sod during wave overtopping conditions. However, the results shown here at not conclusive enough to generate useful results, so they are not part of the main report. First the influence of the thickness of the sod is established. After that, two different factors will be determined to half the number of tests needed for determining the strength of the dike section.

C1   Influence of thickness of the sod

It is interesting to see what the influence of the thickness of the pulled grass sod is. In previous research by Hoffmans, an average thickness was chosen of 5 centimetres. During the tests in the field with the sod pulling machine, the thickness of the sod was measured after it was taken out of the slope. This is not only done in order to find an average thickness, but there also might be a relation between the pulled thickness of the sod and the measured strength to pull out this sod.

In Figure 55a the measured maximum force of all the regular tests are plotted against the measured thickness of the pulled sod. All the locations have a different colour, where all the test methods have a different shape. For example, the yellow rectangles represent the 5 condition 2 tests performed at the Boonweg 2 with the 20x20 frame. Figure 55b shows the same relation but instead of points of data, the same tests at the same locations are plotted as trend lines, in order to make it easier to see the relation between the parameters.
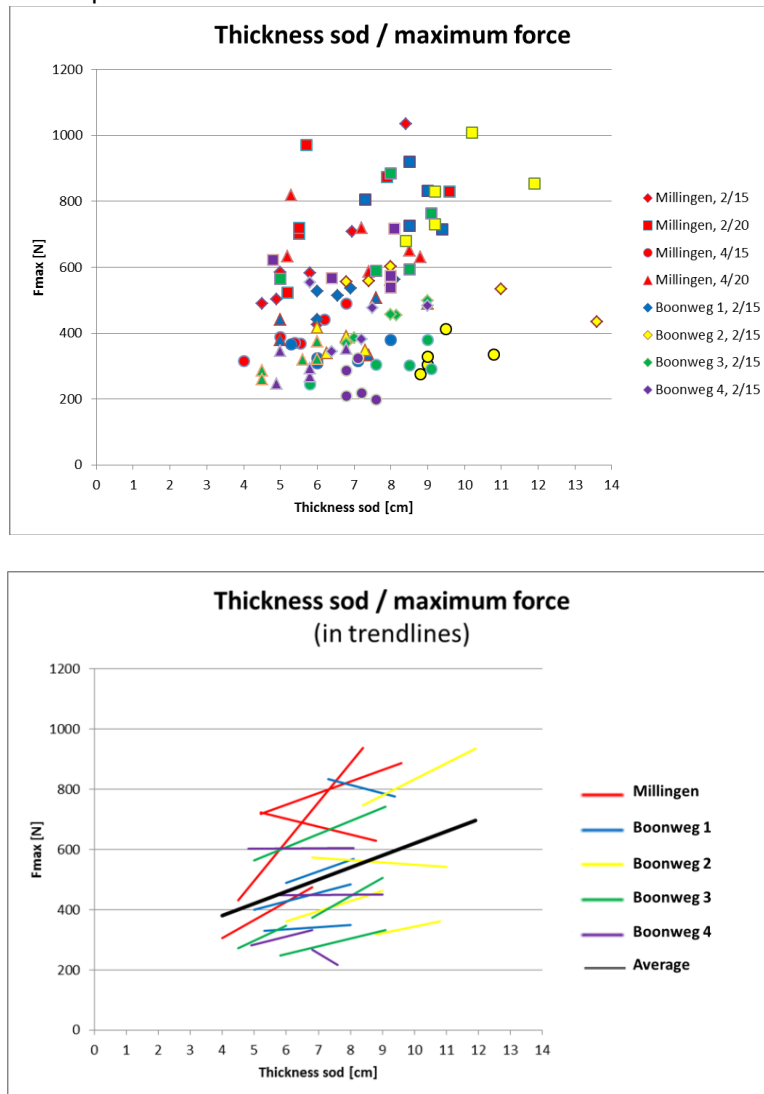

Figure 55 a,b - Measured force as function of the measured thickness in data points (a) and in trend lines (b)

From the graphs follow that the average thickness of the sods is around the 7 centimetres, with a minimum of 4 cm (depth of the pins) and a found maximum of 14 cm. The test of 14 cm thickness had an ant nest at the bottom shear plane, which results in a local weak spot in the depth. This point is neglected because of this.

The dots and triangles are mostly in the lower part of Figure 55a, which makes sense since these represent the condition 4 tests and the sides do not provide extra resistance against the uplifting force. This results in a lower maximum force, but the range of thickness is the same as for the condition 2 tests. One can notice that most of the yellow shapes from Boonweg 2 are present in the right side of the graph, which implies larger thickness of the pulled sod. A larger pulled thickness can depend on the type of grass and herbs in the sod, but additional research is required on this subject. Different types have different root systems, which can lead to different depths for the bottom shear plane.

Most points however, are scattered around the 7 cm thickness, independent of test method and frame size. When the trend lines are revealed per test method and location there is on average a clear upward trend visible (black line in Figure 55b). This relates to an increasing relation between the measured thickness and the force needed to pull out this sod. A thicker sod fails under a larger force. Because of this an average value of 7 centimetres was taken for determining the critical grass mean normal stress of an intact sod. In that calculation, a larger average thickness has influence on the final outcome, since the force has to be divided over a larger area.

Figure 56 shows the relation between the measured thickness and the calculated critical mean normal stress. For the calculation of the stress the practical approach is used, with an average thickness of 7 cm of the grass sod for frame sizes 15x15 and 20x20. All the lines are trend lines through the data points of each individual test. There is on average an upward trend visible.
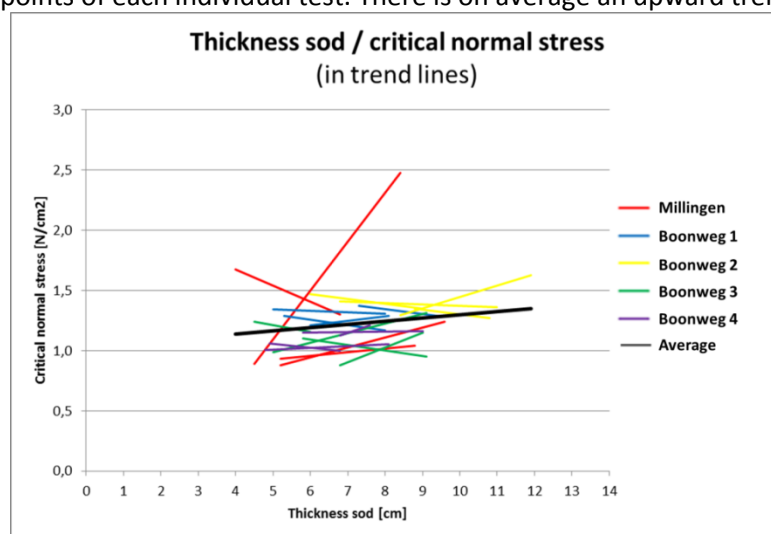

Figure 56 - Critical normal stress as a function of the measured thickness

This figure shows the same behaviour as the Figure 55a and 55b. The overall trend is upward, but also some downward trend lines are visible. These three graphs show the same tests at the same locations and give the same result. A downward slope in the graph with the maximum force corresponds to a downward slope in the graph with the calculated normal stress. This means that the method of calculating the critical mean normal stress is in accordance with the measured force and does not change, due to the relation with the average thickness. The steepness of the trend lines is mostly a bit smaller, but more factors have been used in the calculation of the normal stress. Due to this, the influence of the thickness decreases, which can result in less steep trend lines.

The graphs in this section show on average the above mentioned trend, but when looking at each test method individually, there is sometimes a downward trend present. This is because the thickness is not the only parameter which has influence on the strength of the pulled out grass sod. Also the width and composition can play a role. This can lead to a downward trend in some cases, but the graphs show that the upward trend between the thickness and force or tensile stress is governing.

To conclude: most data points of the measured thicknesses are around 7 cm, there is a cloud of points concentrated around this value. Furthermore, it is possible to take an overall average thickness for calculating the tensile stresses. When using an average thickness of 7 cm for the 15x15 and 20x20 frame the results in line with the expectations.

C2   Factor frame sizes

The influence of the different frame sizes on the coefficient of variation is known, so it is interesting to see what the different sizes have in common. A lot of different tests are performed in Millingen and Friesland, but there might be a recurring relation between different areas of testing. This could result in empirical factors, with which only one frame size needs to be tested, in order to determine the strength of the other frame sizes. This could limit the number of tests necessary to get a good overview of the strength of the dike. The empirical factor will be compared with an estimation of the theoretical factor, to check if they are in the same range. Furthermore if this relation exists, it shows that the theory of a given area relates to the strength. It is expected to be a linear relation ($F \sim m^2$). The factor is computed by sorting the different frame sizes (and sides cut) on size and combining the largest with the largest values and so on. The amplification factor is then computed by dividing the measured force of the larger frame size with the force of the smaller size. Figure 57 and 58 show the amplification factor for different frame sizes, where the factor is plotted on the vertical axis. The horizontal axis represents the location of the data points, where there is a difference made between the condition 2 and 4 tests.
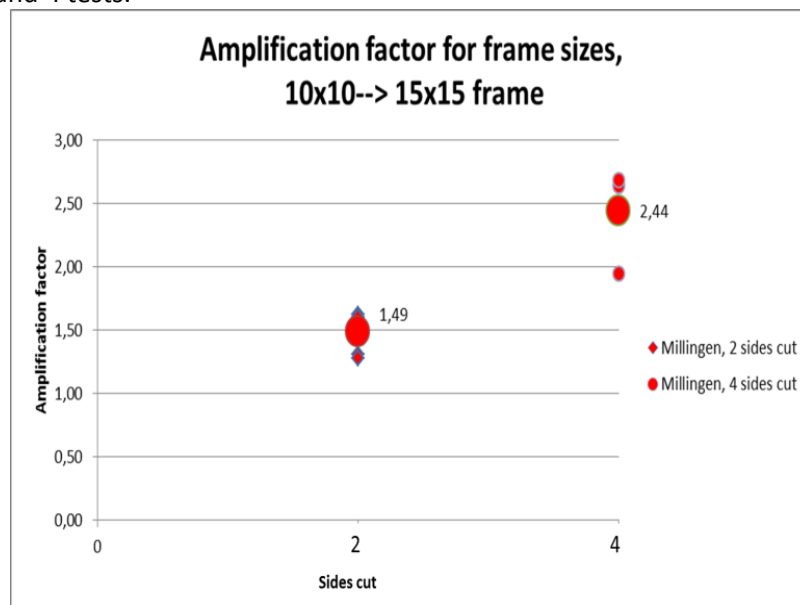

Figure 57 - Amplification factor for increasing one frame size with the data from the 10 by 10 cm frame size
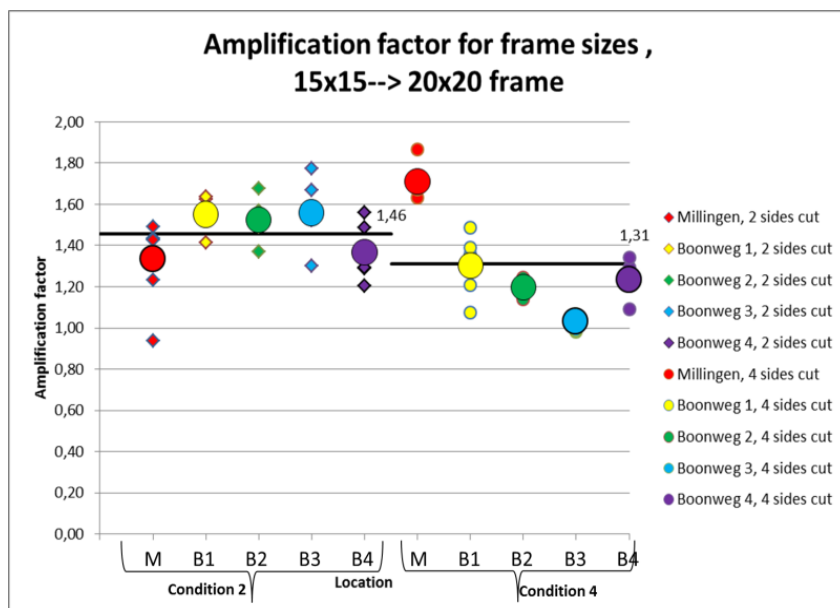
Figure 58 - Amplification factor for increasing one frame size with the data from the 15 by 15 cm frame size

The values of the amplification factor for different frame sizes are expected to be higher than one. If the factor is smaller, which is the case in Millingen for one test, the strength of a smaller frame size is higher than for a bigger frame size. This is possible, but not likely since a larger area should have a higher resistance against uplifting. However, due to the coupling and the heterogeneity of the grass, a stronger place and a smaller frame size can result in higher forces compared to a weaker spot with a bigger frame size. Since the averages are the most important values here, this point is neglected.

Different locations have a different type of maintenance, which result in different kind of strengths. But in this case, the factor may not be influenced by this, since it is about the relation between the measured strength of the different frame sizes per location. The influence of different locations cancels out in the factor. So it is expected that the factors of different locations are in the same order for the same type of tests, since they are only influenced by the heterogeneity of the grass.

All these factors can also be estimated from a theoretical point of view. This can be done by looking at the total area of both the tested sod and the area a different frame size. When assumed that a given area corresponds linear to the strength, the difference in area is in the same order as the amplification factor. The assumption is can be valid since a larger area has more roots inside the sod, which leads to a higher strength of the sod. When the estimation is made for the different areas (including the shape factor, see Chapter 6.1) of the corresponding frame sizes, the following factors are expected on the basis of this theory, see Table 21.

Table 21 - Theoretical amplification factor for increasing one frame size with different frame sizes

Frame size	Sides cut	Theoretical
10->15	2	2,1
	4	2,2
15->20	2	1,5
	4	1,7
10->20	2	3,1
	4	3,7

Conclusion

Table 22 compares the theoretical values with the calculated (practical) values from the tests shown in the figure.

Table 22 - Comparison between theoretical and practical amplification factor for different frame sizes

Frame size	Sides cut	Theoretical	Practical	Deviation
10->15	2	2,1	1,5	-29%
	4	2,2	2,4	13%
15->20	2	1,5	1,5	-2%
	4	1,7	1,3	-23%
10->20	2	3,1	2,2	-30%
	4	3,7	3,2	-13%

Figure 57 and 58 show that there is a factor between the frame sizes, but there is some deviation from the average per location. There is a distinction between the factor for 2 sides cut loose and for all sides cut. The factor for 2 sides cut is more constant over different locations, but there is some scatter in the results. The factors to increase one frame size are approximately the same: 1.5. However, this is not in line with the theoretical approach which was assumed, see Table 22. The theoretical increase of the frame size is larger than calculated from the measured results.

The factor for 4 sides cut and different frame sizes is more scattered and does not really show a clear pattern. One would expect that the force would increase linear with the bottom area, especially since no other areas play a role during these tests. This is in general however not the case, the calculated force from the measurements needed is less than expected on the basis of the theory.

Discussion

The difference between the theoretical estimated values and the practical values can be explained by the fact that the estimated area does not exactly correspond to the measured strength. This is because this estimation is based on the assumption that a larger area has more roots in it, which support the sod. But the roots decrease over the depth of the sod, so it is not a pure linear relation. This leads to an overestimation of the theoretical strength factor, which is visible in Table 22. Furthermore, the pins of the pull frame are inserted 4 cm below the surface. This leads to a stress distribution which is not constant over the depth. This is also not accounted for in the theoretical estimated factor.

The condition 2 amplification factor is on average quite constant over the different locations, therefore it is possible to calculate the value for the 20x20 frame size from the 15x15 frame size by multiplying the measured force with 1.5, so $F_{2.15x15} * 1.5 = F_{2.20x20}$. This is not possible for the condition 4 tests, due to the large scatter in the results.

C3   Factor condition 2 and 4

There is another possibility for an empirical factor which can reduce the number of tests. If there is a recurring relation between the 2 and 4 sides cut test, a ratio could be used to calculate the strength of a condition 4 test from condition 2 or the other way around. This could decrease the number of tests which need to be performed by half. Here the measured values per condition (2 or 4) are compared with data from the same location and the other condition. The data are again coupled on size, where the largest condition 2 is compared to the largest condition 4 of that frame size on that location. In Figure 59 the reduction factor is plotted per location and frame size. The horizontal axis represents the location and the frame size.
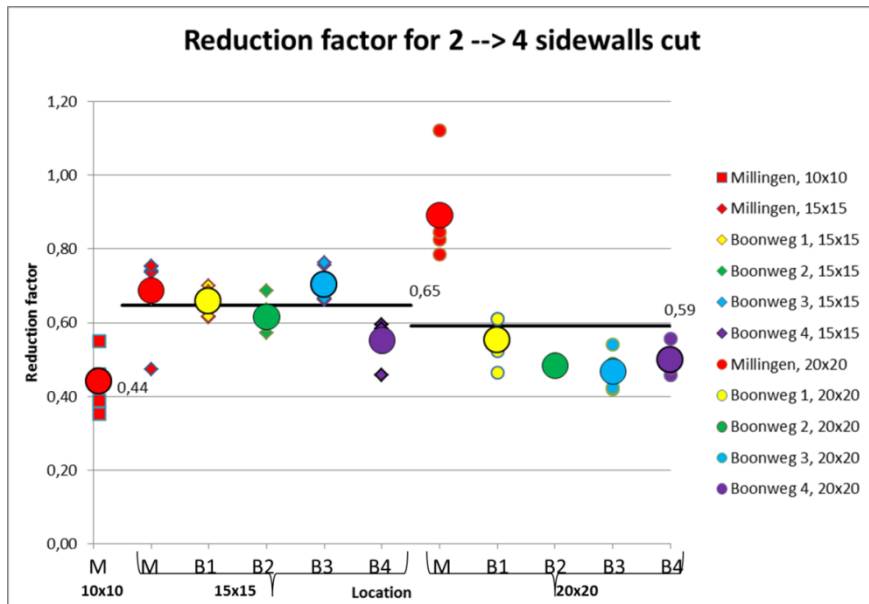
Figure 59 - Reduction factor for condition 2 test towards condition 4 test

When looking at the reduction factor for strength of an intact sod, the values are expected to be lower than one. If the factor is higher, which is the case in Millingen for one test, the strength of a condition 2 test is smaller than the condition 4 tests. This is possible, but not likely since the sides provide extra resistance against the displacement. However, since grass is so heterogenic a stronger place with condition 4 test can result in higher forces compared to a weaker spot with 2 sides still intact. Since the averages are the most important values here, this point is not taken further into account.

Different locations have a different type of maintenance, which may result in different kind of strengths. But in this case, the factor may not be influenced by this, since it is about the relation between the measured strength of the different test conditions per location. The influence of different locations cancels out in the factor. So it is expected that the factors of different locations are in the same order for the same type of tests.

These reduction factors can also be estimated from a theoretical point of view. This can be done by looking at the total area of the tested sod for condition 2 and 4. When assumed that a given area corresponds linear to the strength, the difference in area is in the same order as the factors calculated above. The assumption is valid since a larger area has more roots inside the sod, which leads to a higher strength of the sod. When the estimation is made for the different areas of corresponding frame sizes, the following factors are expected on the basis of this theory, see Table 23.

Table 23 - Theoretical reduction factor for condition 2 test towards condition 4 test with different frame sizes

Frame size	Theoretical
10x10	0,50
15x15	0,52
20x20	0,59

Conclusions

Table 24 compares the theoretical values with the calculated (practical) values from the tests shown in Figure 59.

Table 24 - Comparison between theoretical and practical reduction factor for different frame sizes

Frame size	Theoretical	Practical	Deviation
10x10	0,50	0,44	-12%
15x15	0,52	0,65	24%
20x20	0,59	0,59	0%

Figure 59 shows that there is a factor between the frame sizes, but it is not as clear as expected beforehand. There is a distinction between the factors for the different frame sizes. The factor for the 10x10 frame size is scattered and a bit lower than expected with the theory.

The factor for the 15x15 frame size is more constant over different locations, but there is still some scatter in the results. However the value of this factor is not in line with the theoretical approach which was assumed beforehand. The theoretical decrease in force is much larger than calculated from the measured results as can be seen in the table. So the factor is higher than expected with the theory.

The factor for the 20x20 frame size is most scattered, mostly due to the tests performed in Millingen. But the average is the same as expected from the theory. When the tests in Millingen not taken into account, the practical factor is lower than expected on the basis of the theory.

Discussion

There is no explanation available yet for why the theory is not in line with the calculated values from the measurements. There is also not a clear pattern in the differences, sometimes the theory overestimates the factor, other times it underestimates the value. This can be investigated in additional research, but the 15x15 frame size has given more unusual values for the condition 4 test, especially for the theoretical calculation of the strength of an intact sod (see Chapter 6.2). The strength of the condition 4 test for this frame size is higher than expected with the theory, which results in a larger factor in this case.

One would assume that the theoretical factor should be higher than expected on the basis of the given areas. Since the bottom roots are located at a lower level, there are fewer roots per area due to the decrease of roots over the depth. This would result in a lower practical value than compared with the theoretical factor. This is the case when looking at the 10x10 frame size and the common factor for the 20x20 frame size when neglecting Millingen. This does however not explain why Millingen is much stronger for the condition 4 tests compared to the Boonweg testing. Since the reduction factor is not constant enough, this factor should not be used to reduce the number of tests.

D   Derivation of critical velocity

The current methods of determining the sod quality, divide the grass into the groups very poor, poor, moderate and good, see Chapter 3.1. Research has already been performed in order to link the four groups towards a critical velocity. This is however done on the basis of different parameters per quality and not as an exact science. The derivation of the current methods towards the critical velocity is given below. This is based on a combination of three papers (Hoffmans *et al.,* 2008, 2010 and 2012). A summary of this section is used in the main report in order to keep the reader on track of the most important equations.

D1   Strength of the soil

The strength of the soil can be described by the Mohr Coulomb equation, which describes soil failure in terms of shear- and normal stress along a sliding plane. When also the grass with its roots is taken into account, it can be combined into Equation 43.

$$\tau_s = c_e \cos \phi_e + c_r + (\sigma - p_w)sin\phi_e \tag{43}$$

In this equation is τ_s the soil shear stress, c_e the effective soil cohesion, p_w the pore water pressure, σ the soil normal stress and ϕ_e represents the effective angle of internal friction. The strength of the roots is represented by the root cohesion c_r.

In order to determine the effect of the root reinforcement by grassland vegetation the root equation of Wu *et al.* (1979) is used. Here the mean root tensile stress and mean root diameter are used as input variables. Since roots do not grow solely horizontal or vertical, the root tensile stress can be resolved in factors parallel and perpendicular to the plane of shear, see Figure 60. So c_r can be determined as follows.

$$c_r = \frac{A_r}{A}\left(\sigma_{root,v}\,tan\phi + \sigma_{root,h}\right) = \sigma_{root}\,\frac{A_r}{A}(cos\theta tan\phi + sin\theta) \tag{44}$$

In this equation is the factor A_r / A known as the Root Area Ratio (or RAR), which is a factor for the total area of all the roots combined in 1 m². The angle of shear rotation is given by θ, which is estimated to be between 45° and 70°. Since the angle of internal friction varies between 30° and 40°, the equation can be simplified for almost all values of ϕ and θ towards
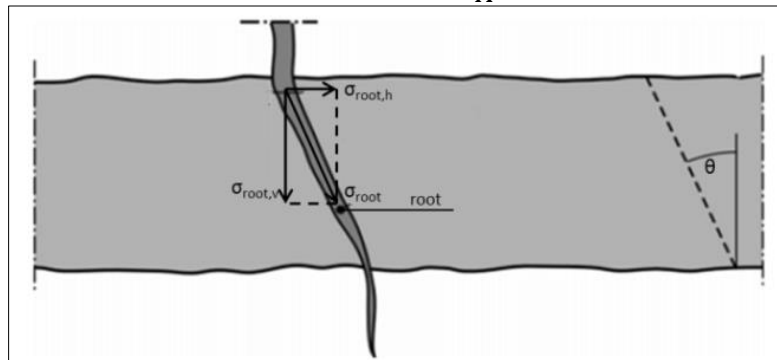
$$c_r = 1{,}2\sigma_{root}\,\frac{A_r}{A} \tag{45}$$

Figure 60 - Root structure in a sod (Hoffmans, 2012)

The root cohesion is correlated with the grass tensile stress σ_{grass}, where both parameters do not include the friction of roots on clay. Since not only the vertical roots provide resistance against vertical motion, also the horizontal roots have impact on the strength. Because of this the mean grass normal stress is approximated by the same type of equation.

$$\sigma_{grass} = \frac{A_r}{A}\left(\sigma_{root,v} + \sigma_{root,h}tan\phi\right) = \sigma_{root}\,\frac{A_r}{A}(cos\theta + sin\theta tan\phi) \tag{46}$$

A problem with the estimated c_r and σ_{grass} is that the equation assumes that all the roots break and they do it simultaneously. From field tests it has become clear that this is not the case, they break at

different elevations and some roots are pulled out of the remaining sod. Because of this, the outcomes of the equations lead to an overestimation of c_r and σ_{grass}.

The critical mean root tensile stress is dependent on the type and quality of the grass layer. Sprangers (1999) examined grass parameters on 24 Dutch dikes, where special interest was paid towards the root length and the RAR. He found that the Root Area Ratio decreases exponentially with the depth and two third of all the roots are found in the top 10 centimetres. In the top 20 centimetres 75% of the roots are found. This led to Equation 47 and 48 for the critical grass normal stress on ground level as a function of the depth.

$$\sigma_{grass,c}(z) = \sigma_{grass,c}(0)\exp(\frac{z}{\lambda_{ref}}) \tag{47}$$

$$\sigma_{grass,c}(0) = \frac{A_r(0)}{A}\sigma_{root,c} \tag{48}$$

These equations are also the basis for estimating the strength of an intact sod with the theoretical approach of Hoffmans, which is used in Chapter 6.2.

D2   Turbulence

The strength of the grass has been determined, it is possible to look further into the loads on the grass sod. When the overtopping wave is rolling down the slope, considerable turbulence will occur due to the irregularities in the sod. When small aggregates are washed away, these irregularities will even increase further, leading to more turbulence. The bed roughness is characterized by the Chézy coefficient (C).

$$U_0 = C\sqrt{R_h S_b} \tag{49}$$

Where U_0 is the depth averaged flow velocity, R_h the hydraulic radius which is equal to the flow depth and S_b is the slope of the dike. The depth averaged relative turbulence intensity (r_0) is defined by Hoffmans et al. (2008)

$$r_0 = \frac{\sqrt{k_0}}{U_0} \tag{50}$$

With

$$k_0 = \frac{1}{h}\int_0^h \frac{1}{2}\left(\sigma_x^2(z) + \sigma_y^2(z) + \sigma_z^2(z)\right)dz \tag{51}$$

In these formulations is h the flow depth, k_0 the depth averaged turbulent kinetic energy and σ the standard deviation of the fluctuating velocity in each direction. This can be simplified (Graf 1998) towards

$$\sqrt{k_0} = \alpha_0 u_* \tag{52}$$

Where α_0 is a constant with a value of 1.2. The relative turbulence can be rewritten, with u_* as the bed shear velocity given by $u_* = \sqrt{gR_h S_b}$, into

$$r_0 = \frac{\alpha_0 u_*}{U_0} = \frac{\alpha_0 \sqrt{g}}{C} \tag{53}$$

This results in relative turbulence intensity between 0.1 and 0.3, assuming a maximum flow velocity of 8 m/s and flow depths between 2 and 40 cm.

The maximum lowering of the local pressure caused by eddies (p_m) is based on research from Emmerling (1973), who investigated the instantaneous structure of the pressure near the bed under turbulent flow conditions. He discovered that the largest eddies, which are between 0.15 cm^{-1} (on macro scale) and 1.5 cm^{-1} (on micro scale), contribute most to the lift force. The standard deviation of this pressure is about three times the mean bed shear stress and the maximum pressure could be up to six times the standard deviation. So the maximum pressure peaks can be written as a function of the mean bed shear stress (τ_0) and is equal to

$$p_m = \alpha_\tau \tau_0 = 18\,\tau_0 \tag{54}$$

When using the relative turbulence equation, it can be rewritten as

$$\tau_0 = \alpha_0^{-2}\rho(r_0 U_0)^2 = 0.7\rho(r_0 U_0)^2 \tag{55}$$

This in turn results in

$$p_m = \alpha_0^{-2}\alpha_\tau \rho(r_0 U_0)^2 = 12.5\rho(r_0 U_0)^2 \tag{56}$$

From this equation follows that (with the same assumptions) the maximum pressure on the bed is around 50 kN/m^2 (or 5 N/cm^2).

D3 Turf Element Model

The Turf Element Model tries to link the strength with the load on the grass sod (Hoffmans, 2012). This model is based on a saturated turf aggregate with the dimensions of a cube, see Figure 61. On this cube two kinds of forces can be distinguished, the load forces due to pressure fluctuations perpendicular to the grass cover (caused by overtopping waves for example) and the strength factors of the soil.
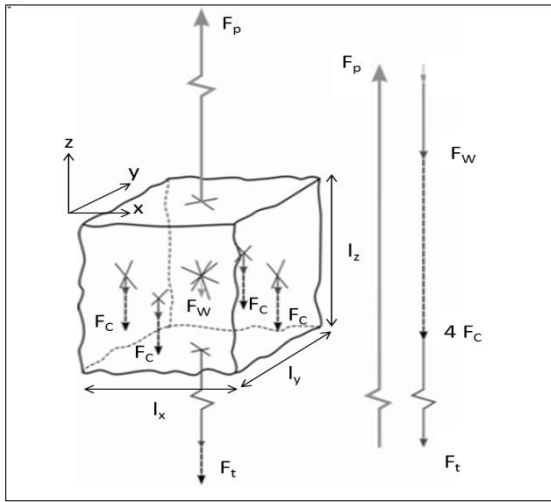

Figure 61 - Turf Element Model schematization (Hoffmans 2012)

In Figure 61 is the cube shown with the lengths l_x, l_y and l_z in the x, y and z direction respectively. Movement of the aggregate is expected when the load is larger than the strength, so

$$F_p \geq F_w + 4\,F_c + F_t \tag{57}$$

$$4\,F_c = 2(1-n)(C_{clay,c} + \tau_{grass,c})(l_x + l_y)l_z \tag{58}$$

$$F_p = p_m l_x l_y \tag{59}$$

$$F_t = (1-n)(C_{clay,c} + \sigma_{grass,c})l_x l_y \tag{60}$$

$$F_w = (1-n)(\rho_s - \rho)g l_x l_y l_z \tag{61}$$

In these equations is F_p the maximum lift force and F_w the submerged weight of the soil. F_c is the critical friction force acting on one side, which depends on the rupture strength of clay $C_{clay,\,c}$ and mean grass shear stress $\tau_{grass,\,c}$. Furthermore, F_t is the critical mean tensile force on the bottom plane. p_m represents the maximum lowering of the local pressure caused by the eddies in the overtopping wave.

When applying $l_x = l_y = l_z = -z$ on the above equation, it can be rewritten as

$$p_m \geq \sigma_{soil}(z) = -(1-n)[(\rho_s - \rho)gz - 4(C_{clay,c} + \tau_{grass,c}) - (C_{clay,c} + \sigma_{grass,c}(z))] \tag{62}$$

In this equation $\sigma_{soil}(z)$ is the soil normal stress as a function of the depth z.

When particles start to move, the horizontal forces are usually considered. When τ_0 reaches the critical mean bed shear stress τ_c, turf aggregates will start to move. The movement of these particles can best be described with the critical Shields parameter Ψ_c. This parameter has a value between 0.03 and 0.06 for larger particles in turbulent flow.

Since grass sods can easily resist compression forces, only tensile stresses will lead to failure of the sod. This leads to the following equation for incipient motion of aggregates, where z is replaced with $-\lambda_{ref}$.

$$\tau_0 \geq \tau_c = \Psi_c\left[(\rho_s - \rho)g\lambda_{ref} + 4(C_{clay,c} + \tau_{grass,c}) + (C_{clay,c} + \sigma_{grass,c}(-\lambda_{ref}))\right] \tag{63}$$

The submerged weight of the soil and the strength of the clay are in the order of 5% of the strength of the grass, therefore they can be neglected for simplicity. This results in the following equation.

$$\tau_0 \geq \tau_c = \Psi_c\left[4\,\tau_{grass,c} + \sigma_{grass,c}(-\lambda_{ref})\right] \tag{64}$$

The strength is determined by the roots in the four sides and the bottom of the cube. Since grass roots have the same properties in the length direction, the shear strength (side roots) and the tensile strength (bottom roots) can be expressed relative to each other. The most important thing to take

into account is the exponential decrease of roots over the depth. These formulations are again also used for the estimation of strength of an intact sod by Hoffmans.

$$\tau_{grass,c} = \frac{1}{\lambda_{ref}} \int_{-\lambda_{ref}}^{0} \sigma_{grass,c}(z)dz \tag{65}$$

Or

$$\tau_{grass,c} = \frac{\sigma_{grass,c}(0)}{\lambda_{ref}} \int_{-\lambda_{ref}}^{0} \exp(\frac{z}{\lambda_{ref}}) \tag{66}$$

Or

$$\tau_{grass,c} = \alpha_{grass}\sigma_{grass,c}(0) \tag{67}$$
$$\text{with } \alpha_{grass} = 1 - \exp(-1) = 0.64$$

Since the critical grass shear strength does not depend on $-\lambda_{ref}$ in these formulations, the strength equation can be rewritten into

$$\tau_0 \geq \tau_c = \alpha_{grass,\tau} \Psi_c \sigma_{grass,c}(0) \tag{68}$$
$$\text{with } \alpha_{grass,\tau} = (1 + 3\alpha_{grass}) = 2.9$$

D4   Critical velocity

When assumed that the overtopping wave generates a hydraulically rough flow and the start of motion is given as $U_0 = U_c$ the critical depth-averaged velocity of fully saturated grass can be calculated with

$$U_c = \alpha_{grass,U} \; r_0^{-1} \sqrt{\frac{\Psi_c \; \sigma_{grass,c}(0)}{\rho}} \tag{69}$$

With

$$\alpha_{grass,U} = \alpha_0 \sqrt{(1 + 3\alpha_{grass})} = 2.0 \tag{70}$$

However, since the previous equation assumes a fully saturated state of the sod, a small adjustment can be made in order to incorporate the saturation of the sod. The saturation will increase over time during overtopping waves, to which the suction pressures will reduce to zero. But since the suction pressure in the unsaturated soil can increase the strength of the top soil, it must be included in the equation. The pore water pressure p_w represents the suction pressure in the roots and has a negative sign (for example -10 kN/m^2).

$$U_c = \alpha_{grass,U} \; r_0^{-1} \sqrt{\frac{\Psi_c \; (\sigma_{grass,c}(0) - p_w)}{\rho}} \tag{71}$$

This indicates that the critical velocity is proportional to the square root of the grass normal strength.

E Statistical analyses of intact grass sod

For the calculated values from the practical approach, a distribution has to be assumed in order to determine the weakest spots on the slope. The data itself give some insight into the weaker spots, but when a distribution is assumed, a certain percentage of a minimum value can be determined. There are different distributions possible, but here the normal distribution will be investigated. In the next section the parameters (μ and σ) will be determined of this distribution.

E1 Normal distribution

In Figure 62 (a-e) on the next page, the calculated values for the critical mean grass normal stress are plotted against their occurrence relative to each other. In grey is a normal distribution plotted for comparison. This is done for all five locations. Furthermore, Figure 62f shows the combination of all the plots.

It can be seen from the figures that the critical mean normal stress is similar to a normal distribution. The figures are based on 20 to 25 measurements, so there is not an exact correlation, but it seems to behave in the same pattern. Millingen is the least in agreement with the normal distribution, but the measurements from the Boonweg show a clearer correlation. So it is assumed that, given enough measurements, a grass sod is normally distributed. The normal distributions are positive for all the values, although the distribution of Millingen approaches zero. Special attention will be paid to Millingen in the next section, when the parameters of the distribution will be determined.

Research from Alterra showed that individual roots have different strength distribution, where the standard deviation is in the same order as the average. Because of this, a normal distribution is not possible, since it will lead to negative values. Therefore, Alterra uses a lognormal distribution for the strength of the individual roots. But since this is not the case for the calculated stresses for an intact sod, the normal distribution is allowed and used.
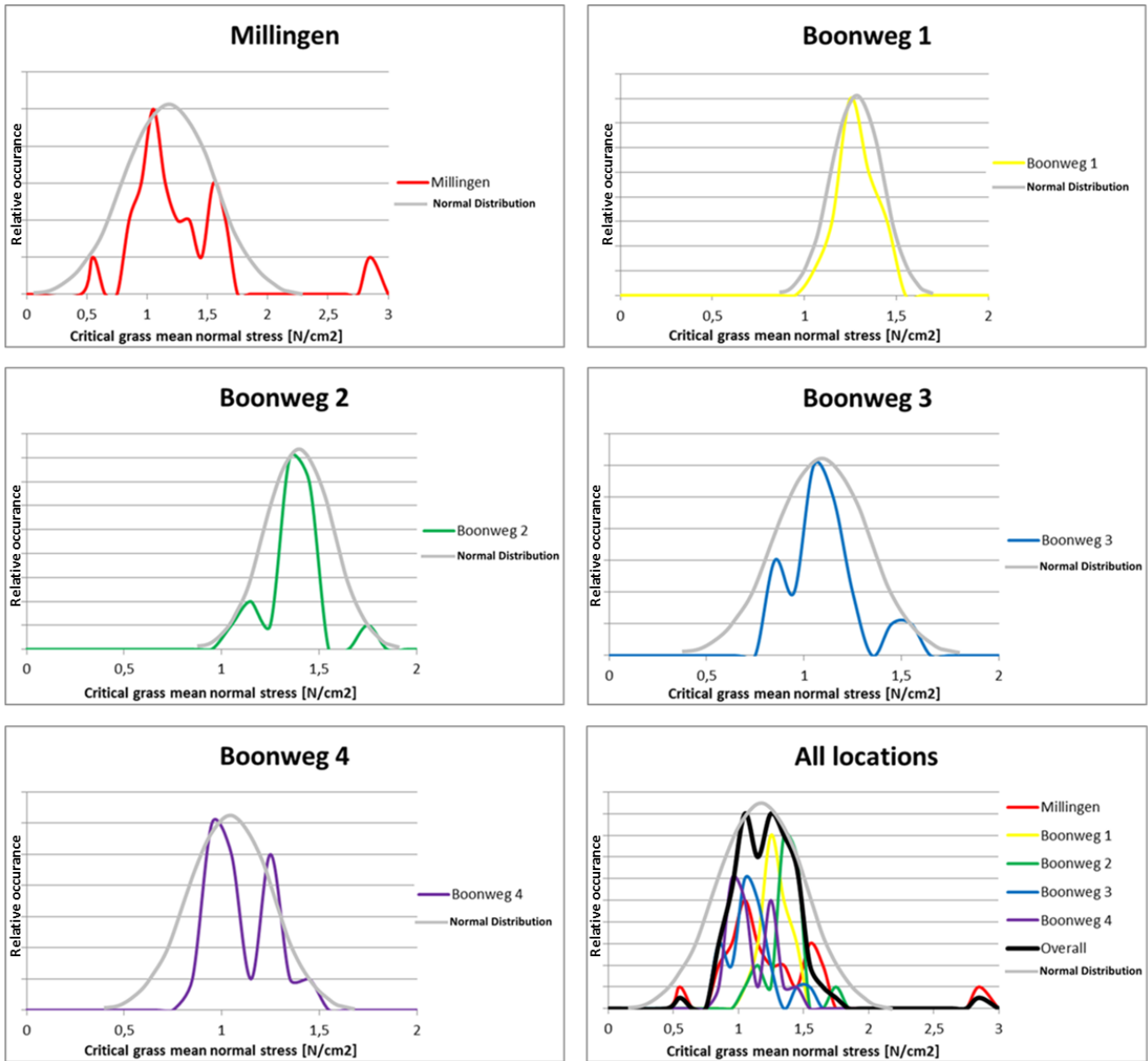
Figure 62 a,b,c,d,e,f - Comparison of strength distribution per location and a given normal distribution

E2   Standard deviation

In the previous section it was determined that the critical grass mean normal stress is normally distributed. Here, the parameters μ and σ will be determined for the different locations. This is performed in two different ways:

1. The first approach is calculating the average and standard deviation in the conventional way, with the following equations

$$\sigma = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(x_i - \mu)^2} \quad with \quad \mu = \frac{1}{N}\sum_{i=1}^{N}x_i \tag{72}$$

In Millingen there is one point which is much stronger than all the other points. When this point is used in the analyses, the μ and σ will give less correct values for Millingen. The standard deviation will increase by a factor of 1.5. Since this one value is much higher (and the governing points are the weak spots), this point can be neglected in the analyses in order to give more accurate results for the weakest spots.

When the μ and σ are calculated with the above equation, it leads to the values for the critical grass mean normal stress shown in Table 25.

Table 25 - Calculated standard deviation

	µ	σ	Cv
Millingen	1,18	0,27	23%
Boonweg 1	1,28	0,10	8%
Boonweg 2	1,37	0,14	10%
Boonweg 3	1,10	0,17	16%
Boonweg 4	1,10	0,14	12%

2. The second method of determining the standard deviation of the distribution is performed by plotting all the computed values of the critical grass mean normal stress in one figure per location. This is done in Figure 63 (a-e). The points are scattered around an average value μ, which is again computed by Equation 72. All these data points can be used to give an estimate of the standard deviation (the grey line in the figure). Since the grass is assumed to be normally distributed, a certain percentage of the points outside a certain range can be used for determining the standard deviation. Normal distributions assume that if 10% of the points (5% at each end) are outside a given range, the value at this border is equal to 1.64 σ. The same applies for the border at approximately 32% of the points (16% at each end), which leads to a distance 1 σ from the average. When this is applied to the points in the Figure 63, it gives the four lines with estimated standard deviations, which are averaged to one value for the standard deviation of the critical grass mean normal stress shown in Table 26.

Table 26 - Determined standard deviation

	µ	σ	Cv
Millingen	1,18	0,29	34%
Boonweg 1	1,28	0,11	8%
Boonweg 2	1,37	0,17	10%
Boonweg 3	1,10	0,18	16%
Boonweg 4	1,10	0,14	12%

When the two methods are compared, it becomes clear that they give both approximately the same results. There are small differences between both methods, but the second method is less accurate with few data points. Because of this, the computed values from the first method will be used in further calculations.
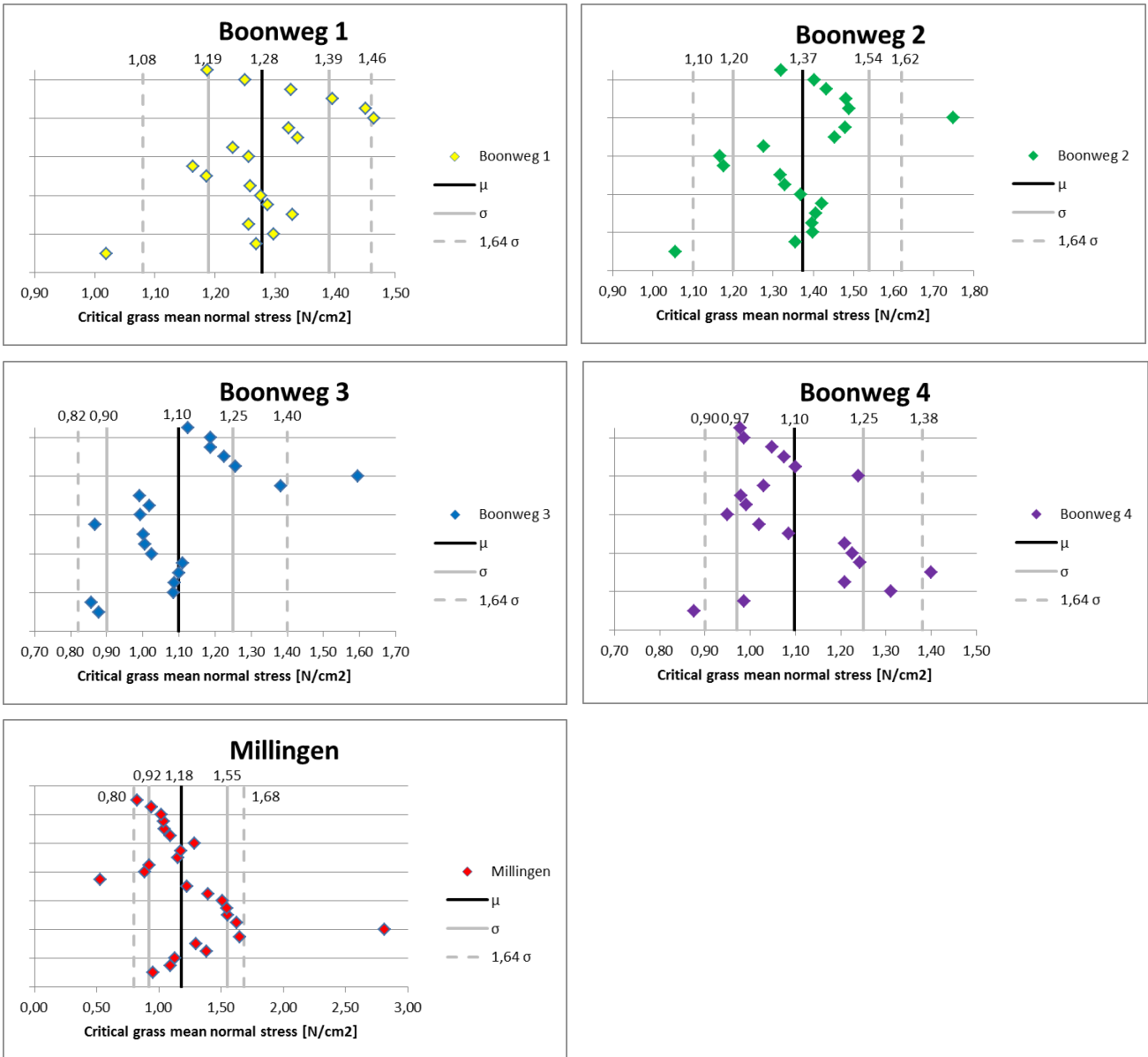
Figure 63 a,b,c,d,e - Plots of estimations of the standard deviation per location by the method of lines