GRASS SOD PULLING TESTS TO DETERMINE THE EROSION RESISTANCE AGAINST WAVE OVERTOPPING OF VARIOUS TYPES OF GRASS COVERS: AN ADJUSTED ANALYSIS METHOD

Roy Mom[1], Gosse Jan Steendam[2], Rens van der Meijden[3], Jord Warmink[4], André van Hoven[5],
Jentsje van der Meer[6]

The erosion resistance of a grass cover against wave overtopping is characterized by the critical flow velocity. This velocity can be determined with full-scale tests with the wave overtopping simulator. However, a grass sod pulling test requires less effort and can also give a good estimation of this velocity. Within the project Future Dikes several inconsistencies were found in the analysis method used to estimate the critical flow velocity with a grass sod pulling test. To deal with these inconsistencies an adjusted analysis method was proposed. A comparison of the critical flow velocity found with wave overtopping tests and both the original and the adjusted analysis method showed that the adjusted analysis method performs better for non-failed grass covers. The original analysis method, on the other hand, performs better for failed grass covers. The reason for the difference in performance remains unclear and is subject for further research. For now it is recommended to use both analysis methods next to each other when estimating the strength of a grass cover.

Keywords: wave overtopping, dike, grass cover, grass sod pulling test, critical flow velocity

INTRODUCTION

Dikes are usually built to protect the hinterland against flooding from the sea, a lake or a river. These dikes are often constructed of sand and/or clay and have a slope on both the sea- and landside. To protect the core of these dikes against erosion these slopes are covered with a dike revetment. The revetment of the crest and landward dike slope is often a grass cover.

During a storm wave overtopping may cause damage to and ultimately lead to failure of the grass cover. The erosion resistance of the grass cover against wave overtopping is characterized by the critical flow velocity. This velocity is used in the erosion model for safety assessments and the design of the crest height of dikes, as discussed in this paper.

The critical flow velocity of a grass cover can be determined with full-scale tests with the wave overtopping simulator. Although it is considered the most realistic method to assess the strength of a grass cover, a wave overtopping test requires a substantial effort. To avoid this, a small and easy to perform test was developed: a grass sod pulling test. With this test and a corresponding analysis method an estimation of the critical flow velocity can be obtained.

Recently, several inconsistencies were found in the original analysis method. In order to deal with these inconsistencies Van der Meijden (2024) proposed an adjusted analysis method and validated it within the project Future Dikes. This method was applied to the results of more recent tests with both the WOS and GPT. The performance of the adjusted analysis method is presented in this paper.

WAVE OVERTOPPING AND THE CUMULATIVE OVERLOAD METHOD

During wave overtopping the overtopping water – random in time, space and volume – flows at a certain velocity over the crest and the landward slope. The water flow causes shear stresses and pressure gradients at the dike cover surface. This causes material to wash from the surface and out of the grass cover. Sometimes the grass sod is (partially) torn loose, causing the grass sod to strip. The soil layer below is then exposed and can therefore erode. If the grass cover has not yet failed, the roots in this cover layer still have a considerable influence on the degree of erosion. When the influence of the roots becomes less significant at a depth of 0.2-0.3 m the grass cover is considered to have failed for an erosion hole at this depth.

Full-scale tests with the wave overtopping simulator (WOS) have been conducted since 2007 (Van der Meer et al. 2007). These wave overtopping tests have shown that the repeated simulation of overtopping waves that exceed a certain volume or speed, lead to damage and eventual failure of the grass cover. This has led to a method to predict grass cover failure: the so-called cumulative overload

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[1] Infram Hydren, roy.mom@infram-hydren.nl

[2] Infram Hydren, gosse.jan.steendam@infram-hydren.nl

[3] University of Twente, r.vandermeijden@utwente.nl

[4] University of Twente, j.j.warmink@utwente.nl

[5] Deltares, andre.vanhoven@deltares.nl

[6] Van der Meer Consulting; IHE Delft, jm@vandermeerconsulting.nl

method (COM). The preliminary version of this method was developed by Van der Meer et al. (2010) and later extended to include transitions and objects (Steendam et al. 2014, Hoffmans et al. 2018). The cumulative overload can be determined with the following equation:

$$D = \sum_{i=1}^{N} \max[(\alpha_M(\alpha_a U_i)^2 - \alpha_S U_c^2); 0] \qquad (1)$$

Where D [m^2/s^2] is the cumulative overload or damage number, N [-] is the number of overtopping waves, i [-] is the number of the overtopping wave, U_i [m/s] is the front velocity of the overtopping wave, α_a [-] is a factor for acceleration of the front velocity of the overtopping wave along the slope and U_c [m/s] is the critical flow velocity of the grass cover. Note that in case of transitions or objects the factors α_M [-] and α_S [-] can be used to respectively increase the load or reduce the strength.

In COM, the strength of a grass cover is characterized by the critical flow velocity. If this velocity is repeatedly exceeded by the front velocity of overtopping waves, the damage number increases. If the damage number exceeds 7,000 m^2/s^2 during a storm, the grass cover is assumed to fail (Hoffmans et al. 2018). Note that this method is calibrated for predicting failure of the grass cover and is therefore less suitable for predicting other damage.

WAVE OVERTOPPING TESTS

The WOS, see Figure 1, has been used to perform wave overtopping tests on real dikes in The Netherlands, Belgium and Singapore (Van der Meer et al. 2010 and 2020, Steendam et al. 2011 and 2014).

Figure 1. Wave overtopping tests on a real dike in the Carel Coenraadpolder in 2023. The yellow wave overtopping simulator (WOS) is placed on top of the dike crest facing the slope.

The WOS is used to simulate overtopping waves during the peak of a storm. The individual volumes of the simulated overtopping waves are calculated in accordance with the theoretical distributions of overtopping wave volumes in EurOtop (2018) depending on assumed wave conditions and crest freeboard.

In Table 1 an overview is given of wave overtopping tests performed with the WOS. Note that for the tests in Singapore a new WOS was developed. This WOS was also used for the tests in 2022, 2023 and 2024. For the tests in 2021 the wave run-up simulator (Steendam et al. 2016) was used instead of the WOS.

Table 1. Wave overtopping tests during the years.

Year	Country	Location	Substrate	Vegetation
2007	The Netherlands	Delfzijl	Clay	Traditional grass cover*
2008	The Netherlands	Boonweg	Clay	Traditional grass cover*
2008	The Netherlands	Sint Philipsland	Clay	Traditional grass cover*
2008	The Netherlands	Kattendijke	Clay	Traditional grass cover*
2009	The Netherlands	Afsluitdijk	Clay	Traditional grass cover*
2010	Belgium	Tielrode	Clay	Traditional grass cover*
2010	The Netherlands	Vechtdijk	Sand	Traditional grass cover*
2013	The Netherlands	Nijmegen	Clay	Traditional grass cover*
2013	The Netherlands	Millingen	Clay	Traditional grass cover*
2011	The Netherlands	Tholen	Clay	Traditional grass cover*
2014	The Netherlands	Noord-Beveland	Clay	Traditional grass cover*
2020	The Netherlands	Zwolle	Sand/Clay	Traditional grass cover*
2020	Singapore	Pulau Tekong	Clay	Tropical grass cover**
2021	The Netherlands	Vechtdijk	Sand	Traditional grass cover*
2022	The Netherlands	Hedwigepolder	Clay	Traditional grass cover*
2023	The Netherlands	Balgoij	Sandy clay	Species-rich grass cover***
2023	The Netherlands	Lelystad	Boulder clay	Traditional grass cover*
2023	The Netherlands	Carel Coenraadpolder	Clay	Species-rich grass cover****
2024	The Netherlands	Slachtedijk	Clay	Species-rich grass covers****
2024	The Netherlands	Eemshaven	Clay	Species-rich grass covers****

* D1 (a mixture of Lolium perenne, Poa pratensis, Festuca rubra tricho, Festuca rubra rubra and Trifolium repens)
** Cynodon dactylon and Zoysia matrella
*** Mix of traditional grass cover and herbs
**** D1 and different mixtures of Festuca rubra rubra, Festuca rubra commutate, Lolium perenne, Poa pratensis with Festuca arundinacea/Trifolium repens/Herbs (i.e. Achillea Milefolium and Plantago landelotta)

GRASS SOD PULLING TESTS

Full-scale wave overtopping tests are considered to be the most realistic available method to assess the erosion resistance of a dike grass cover. However, these tests require a substantial effort to perform. In order to estimate the critical flow velocity with a small and easy to perform test, a grass sod pulling test (GPT) was developed in 2013 (Steendam et al. 2014). The device used for these tests (Figure 2) was upgraded in 2019 and consists of an actuator that is controlled by an electric motor so that the sod is pulled at a constant speed. While pulling the grass sod, the force needed to lift the sod is recorded.

Figure 2. A GPT with the upgraded device (left picture). The pull frame is attached to the grass sod with steel pins (right).

To perform a GPT the actuator from the grass sod pulling device is connected to a metal 20 cm by 20 cm pull frame. This frame is attached to the grass sod with steel pins at 4 cm below the surface (Figure 2). To place the frame, first a mold is placed over the grass sod to be pulled. Because this mold has two cutting edges, the two opposite sides of the grass sod are cut loose beforehand and soil is dug out on these two sides in order to install the steel pins (Figure 2).

ORIGINAL ANALYSIS METHOD

After pulling the grass sod, the maximum tensile force F_{upward} [N] is determined, the force at which the grass sod fails. Since 2018, F_{upward} is corrected for the own weight of the pulled grass sod. This corrected force is then converted to the tensile force of an intact grass sod F_{intact} [N] (after all, the sides that were cut loose when placing the frame also contribute) by multiplying F_{upward} by an amplification factor AF [-]. A value of 1.56 recommended in Bijlard et al. (2017) can be used for this AF, but this value can also be determined on the basis of additional tests in which all four sides of the grass sod have been cut loose.

The found F_{intact} is then converted to a critical normal stress at ground level $\sigma_{grass,c}(0)$ [N/cm^2]. Here F_{intact} is divided by the sum of the area (the bottom A_{bottom} [cm^2] and all four sides A_{sides} [cm^2]) of the pulled grass sod:

$$\sigma_{grass,c}(0) = \frac{F_{intact}}{A_{bottom}+A_{sides}} \tag{2}$$

Note that in Bijlard et al. (2017) default dimensions of the grass sod are used to determine the area of the pulled grass sod. Because the thickness and width of the pulled grass sod measured in the field often deviate (significantly) from these dimensions, currently, the real dimensions of the grass sod are used to determine both A_{bottom} and A_{sides}.

Typically, 40 regularly spaced tests are performed within a test plot of 10 m by 15 m, of which 30 and 10 tests are performed with respectively two sides and all sides cut loose. The results of both 2-sided and 4-sided tests are used to determine AF. Only the result of a 2-sided test is used to calculate $\sigma_{grass,c}(0)$.

ESTIMATION OF CRITICAL FLOW VELOCITY WITH ORIGINAL ANALYSIS METHOD

With the prototype of the grass sod pulling device Bijlard et. al (2017) performed a series of tests at locations where wave overtopping tests had been carried out in the past. This ultimately led to an empirical equation with which an estimate of the critical flow velocity can be made based on the results of grass sod pulling tests (Bijlard et al. 2017):

$$U_c = \alpha_{grass,U} r_0^{-1} \sqrt{\frac{\psi_c(\sigma_{grass,c}(0)-p_w)}{\rho}} \tag{3}$$

where $\alpha_{grass,U}$ [-] is a factor with value 2.0, r_0 [-] is the relative turbulence intensity with a value of 0.12 for wave overtopping, ψ_c [-] is the critical Shields parameter with a value of 0.03, $\sigma_{grass,c}(0)$ [N/cm^2] is the (maximum) critical normal stress at ground level, p_w [N/cm^2] is the suction pressure in the topsoil and ρ [kg/m^3] is the water density with a value of 1,000.

If a fully saturated soil is assumed, p_w is negligible and $\sigma_{grass,c}(0)$ is the only variable. In Eq. 3 a design value for $\sigma_{grass,c}(0)$ is used, which takes into account weak spots within the test plot. In Bijlard et al. (2017) the lower limit of the 95% confidence interval (α=0.025) of all critical normal stresses within a test plot was chosen. Further it is assumed that all values of $\sigma_{grass,c}$ are sampled from a normal distribution (a (Student's) t-distribution can be used). With the critical t-value applicable for the number of observations, the design value can then be determined based on the average and standard deviation of $\sigma_{grass,c}$.

Note that Eq. 3 is based on the turf-element model as developed by Hoffmans (2012). This model is based on a balance of forces and considers the vertical forces acting on a cube-shaped turf element during wave overtopping.

RESULTS WITH ORIGINAL ANALYSIS METHOD

Table 2 and Figure 3 show the critical flow velocities for projects in which both wave overtopping tests and grass sod pulling tests with the updated version of the device were carried out. Note that the U_c determined with the wave overtopping tests follow from the available test reports or own analysis.

Table 2. Critical flow velocities obtained from wave overtopping tests ($U_{c,WOS}$) and grass sod pulling tests ($U_{c,GPT}$) compared for the original analysis method. Red values of U_c show grass cover failure.

Location	Test section | Test plot	$U_{c,WOS}$ [m/s]	$U_{c,GPT}$ [m/s]	Number of tests
Zwolle	1 | Plot 1	5.40	5.86	30
Zwolle	2 | Plot 2	5.10	5.22	30
Zwolle	3 | Plot 2	4.00	5.22	30
Zwolle	4 | Plot 2	5.00	5.22	30
Vechtdijk	1-1a | bu_53_3_103	6.40	5.90	30
Vechtdijk	1-1b | bu_53_3_103	5.20	5.90	30
Vechtdijk	1-2 | bu_53_3_103	7.10	5.90	30
Vechtdijk	2-1 | bi_9_1_14	7.40	5.44	30
Vechtdijk	2-2 | bu_9_1_14	5.60	5.49	30
Vechtdijk	3-1 | bi_9_1_18	6.60	5.64	30
Vechtdijk	3-2 | bu_9_1_18	7.30	5.84	30
Hedwigepolder	1 | NL-1	6.10	6.61	15
Hedwigepolder	1 | NL-2	6.10	6.36	15
Hedwigepolder	1 | NL-1+2	6.10	6.55	30
Balgoij	43_1 | 43_2	7.40	7.58	30
Balgoij	43_2 | 43_2	7.20	7.58	30
Balgoij	46_1 | 46_2	6.80	5.79	30
Balgoij	46_2 | 46_2	6.40	5.79	30
Balgoij	48_1 | 48_2	6.90	6.63	30
Balgoij	48_2 | 48_2	6.70	6.63	30
Lelystad	0 | 0_boven (doek)	5.60	5.25	15
Lelystad	0 | 0_onder (doek)	3.80	4.12	15
Lelystad	4 | 4_boven (zonder doek)	7.90	5.24	13
Carel Coenraadpolder	0 | 0	5.54	7.15	9
Carel Coenraadpolder	1 | 1	5.97	7.42	18
Carel Coenraadpolder	2 | 2	5.97	6.42	18
Carel Coenraadpolder	3 | 3	6.68	6.85	18
Carel Coenraadpolder	4 | 4	5.97	6.55	18
Slachtedijk	0 | 0	6.50	6.67	9
Slachtedijk	1 | 1	6.46	5.90	18
Slachtedijk	2 | 2	7.40	5.97	18
Slachtedijk	3 | 3	6.50	6.04	18
Slachtedijk	4 | 4	6.50	5.02	18
Eemshaven	0 | 0	7.28	4.64	9
Eemshaven	1 | 1	6.81	5.96	18
Eemshaven	2 | 2	7.44	6.11	18
Eemshaven	3 | 3	7.44	6.53	18
Eemshaven	4 | 4	7.33	7.15	18

Most of the grass covers tested with the WOS did not fail, so only a minimal proven U_c could be derived from these tests. For most of the grass sod pulling tests the estimated U_c is lower than this value (the values are to the left of the line $U_{c,WOS}$ = $U_{c,GPT}$ in Figure 3). Because the actual U_c will be higher, it is noted that for the tests where the grass cover did not fail, the U_c estimated with the GPT is underestimated. For the tests where the grass sod failed, the GPT provides a good estimate of the U_c estimated.

To eliminate or reduce the underestimation of estimated critical flow velocity by the GPT the analysis has been reviewed by Van der Meijden (2024). Next the method has been adjusted according to this findings.

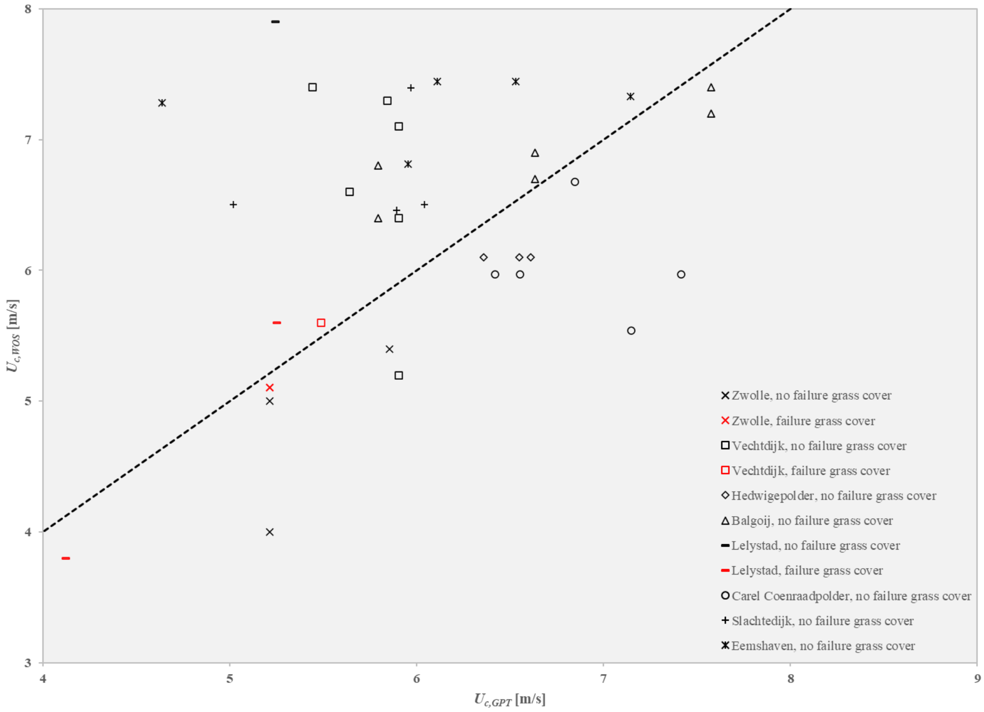

Figure 3. Critical flow velocities obtained from wave overtopping tests ($U_{c,WOS}$) and grass sod pulling tests ($U_{c,GPT}$) using the original analysis method.

ESTIMATION OF CRITICAL FLOW VELOCITY WITH ADJUSTED ANALYSIS METHOD

Within the project Future Dikes (more) knowledge has been developed about the strength of species-rich grass covers. To do so, both wave overtopping and grass sod pulling tests were conducted on dikes near Balgoij. When determining the strength of the grass cover from the GPT several inconsistencies in the analysis method used to estimate the critical flow velocity were found. To deal with these inconsistencies, three changes to the current method were proposed by Van der Meijden (2024):

1. Inclusion of own weigh grass sod.

   Since 2018 arbitrarily, F_{upward} has been corrected for the own weight of the pulled grass sod. Although the size of the own weight is small compared to F_{upward}, it does contribute to the downward forces during wave overtopping. Therefore, the sods own weight should be included in F_{upward}.

2. Confidence interval based on skewness of sample distribution.

   With a large number of degrees of freedom, a Student's t-distribution is (like a normal distribution) approximately symmetrical around the mean. Data shows that, in most cases, the distribution of the samples within a test plot is right (or positive) skewed, in which the used design value underestimates the weakest spot in the test plot.

   Alternative design values for both skewed and non-skewed sample distributions were examined. An analysis based on random fields showed that for left (or negative) skewed distributions (sample skew is smaller than -0.2) the lower limits of the 98% confidence interval (α=0.01) give a more similar critical flow velocity for both wave overtopping and grass sod pulling tests. For right skewed distributions (sample skew is larger than 0.5) the lower limits of the 90% confidence interval (α=0.05) gives a better match. For all values of skewness between -0.2 and 0.5 the 95% (α=0.025) confidence interval can still be used for determining the design value.

3. Use the design value of F_{intact} to estimate U_c.

   In Eq. 3 the design value of $\sigma_{grass,c}(0)$ is used for estimating U_c. However, this parameter cannot be measured directly. Three alternative methods were considered to get from a measured F_{upward} to a calculated U_c. Two of the three methods still use Eq. 3, but use a different approach to determine $\sigma_{grass,c}(0)$. The third method uses an alternative equation to determine U_c without

$\sigma_{grass,c}(0)$ in which F_{intact} is directly implemented into the vertical force balance used in Hoffmans (2012):

$$U_c = \alpha_0 r_0^{-1} \sqrt{\frac{\psi_c\left(\frac{F_{intact}}{A_{frame}} - p_w\right)}{\rho_w}} \tag{4}$$

where α_0 [-] is a factor with value 1.2, A_{frame} [cm^2] is the area of the pull frame with a value of 400 (20 cm by 20 cm), and all other parameters as defined in Eq. 3.

For all three methods the critical flow velocity U_c was estimated for all test plots. Compared with the U_c obtained from wave overtopping tests, the best accuracy was achieved using Eq. 4. However, there are uncertainties associated with the values of U_c determined from both the wave overtopping and grass sod pulling tests. The presence of spatial and temporal variations between different test sites cannot be ruled out. Consequently, the probability distributions of U_c for traditional grass covers on clay and sand were also examined. Here too, the greatest accuracy is found when using Eq. 4. Therefore, it was recommended to use Eq. 4 when determining the U_c.

When the suggested changes above are taken into account, the U_c based on GPT can be estimated as follows:

- Determine for each test within a test plot F_{upward} and convert this to F_{intact} using AF.
- Determine for all tests within a test plot the mean, standard deviation and skewness of F_{intact}.
- Determine the confidence interval to be used.
- Determine the critical t-value for the confidence interval.
- Determine the design value of F_{intact}.
- Determine the U_c with Eq. 4.

RESULTS OF ADJUSTED ANALYSIS METHOD

Using the adjusted analysis method with proposed three changes as described above, the U_c was calculated again for the tests shown in Table 2. The results are given in Table 3. This table also shows the sample skew and the confidence level used for the calculation of the design value of F_{intact}. Note that the results for the locations Lelystad, Carel Coenraadpolder. Slachtedijk and Eemshaven were not considered in (Van der Meijden 2024) when proposing the changes to the original analysis method.

In Figure 4 the U_c found with the adjusted analysis method is compared with the results of the wave overtopping tests (Table 2). For the wave overtopping tests where the grass cover did not fail, the estimated U_c with the GPT is now overestimated (the values are to the right of the line $U_{c,WOS} = U_{c,GPT}$) in Figure 4). This is more realistic because the U_c from the tests with the WOS is regarded as a lower limit. However, for wave overtopping tests where the grass sods did fail, the estimated U_c does not corresponds anymore.

Table 3. Critical flow velocities obtained from grass sod pulling tests ($U_{c,GPT}$) with the adjusted analysis method.

Location	Test plot	Sample skew	Confidence interval	$U_{c,GPT}$ [m/s]
Zwolle	Plot 1	0.23	95%	6.38
Zwolle	Plot 2	0.42	95%	5.98
Vechtdijk	bu_53_3_103	0.00	95%	6.68
Vechtdijk	bi_9_1_14	1.02	90%	6.07
Vechtdijk	bu_9_1_14	0.25	95%	5.08
Vechtdijk	bi_9_1_18	0.05	95%	8.35
Vechtdijk	bu_9_1_18	0.99	90%	6.79
Hedwigepolder	NL-1	-0.44	98%	7.20
Hedwigepolder	NL-2	1.05	90%	7.35
Hedwigepolder	NL-1+2	0.31	95%	7.21
Balgoij	43_2	-0.42	90%	8.14
Balgoij	46_2	-1.37	90%	8.34
Balgoij	48_2	-0.25	90%	8.33
Lelystad	0_boven (doek)	0.88	90%	6.43
Lelystad	0_onder (doek)	0.14	95%	6.08
Lelystad	4_boven (zonder doek)	-0.02	95%	7.20
Carel Coenraadpolder	0	-0.32	98%	7.17
Carel Coenraadpolder	1	-0.05	95%	8.34
Carel Coenraadpolder	2	0.83	90%	7.78
Carel Coenraadpolder	3	-0.20	98%	7.44
Carel Coenraadpolder	4	0.52	98%	6.60
Slachtedijk	0	0.31	95%	7.26
Slachtedijk	1	0.82	90%	6.19
Slachtedijk	2	2.20	90%	6.87
Slachtedijk	3	0.54	90%	7.06
Slachtedijk	4	0.71	90%	6.01
Eemshaven	0	1.09	90%	5.83
Eemshaven	1	0.94	90%	6.76
Eemshaven	2	-0.06	95%	6.78
Eemshaven	3	0.23	95%	7.85
Eemshaven	4	0.12	95%	7.66

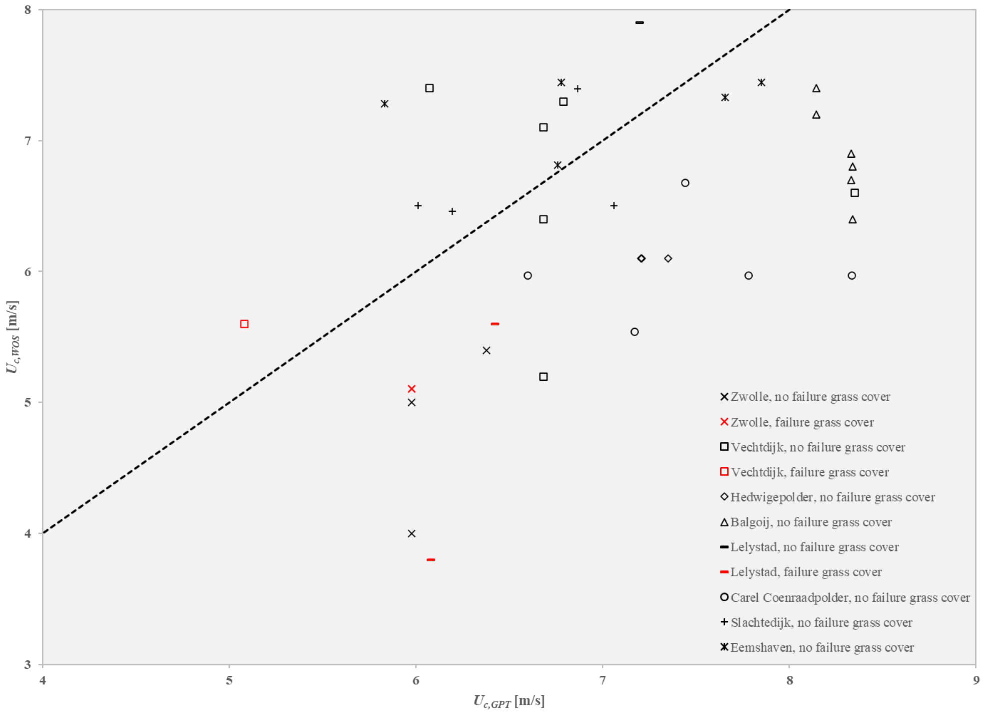

Figure 4. Critical flow velocities obtained from wave overtopping tests ($U_{c,WOS}$) and grass sod pulling tests ($U_{c,GPT}$) compared for adjusted analysis method.

SAMPLE SIZE

When estimating the U_c, the results of all tests within a test plot are usually used: that is 30 tests with two sides cut loose. Van der Meijden (2024) investigated if a good estimate of the U_c can be obtained with fewer samples. Compared with the U_c based on 30 samples (benchmark), at least 20 samples are required for a comparable U_c. This sample size should only be chosen when time and/or budget are limited.

Table 2 shows that the minimal required number of samples is not met for all locations. If the results for these locations are not included in the comparison as shown in Figure 4, only the results for the tests at the Vechtdijk (grass covers on sand) are underestimated.

ORIGINAL OR ADJUSTED ANALYSIS METHOD?

Both analysis methods can be used to estimate the U_c. But which method should be used in future analysis of the strength of a grass cover against wave overtopping? It is hard to give a satisfactory answer to this question. The original analysis method performs better for grass covers that failed during wave overtopping tests. Because full-scale tests with the WOS are used to determine the real strength of a grass cover, this method has an advantage. However, the original analysis method underestimates the U_c for tests in which the grass cover did not fail. For these tests the adjusted analysis method performs better.

It is currently unclear why the U_c estimated with the adjusted analysis method corresponds less with the results of the wave overtopping tests in which the grass sod did fail. It is recommended to look at this in more detail in further research. For now it is recommended to use both analysis methods next to each other when estimating the strength of a grass cover.

FURTHER RESEARCH

For a GPT assumptions were made regarding the width of a test plot, the used pull rate and the loading mechanism. These assumptions may have an effect on both F_{upward} and the estimated U_c with both analysis methods. It is therefore recommended to study the effects of:

- the area of the test plot. Performing the same amount of tests over a larger area with the same characteristics (e.g. management and maintenance, exposition of the slope, vegetation and substrate) may give better insight in the distribution of the maximum tensile force.
- the used pull rate. For saturated soils the pull rate may have effect on F_{upward}. Performing tests with different pull rates and saturation conditions may provide insight in the validity of the pull rate that is currently used (1 cm/s).
- the loading mechanism used. For a GPT the mechanism of maximum force loading is used. Although this loading mechanism gives reasonable results, it differs from the more cyclic loading of the grass cover during the tests with the WOS. The use of a cyclic loading mechanism may give better results. For cyclic loading it is however necessary to know which tensile force a certain overtopping volume applies on a grass sod (possibly a numerical model can provide more insight). More research on the loading mechanism is needed.

In both analysis methods assumptions are made with respect to the saturation of the soil and turbulence. Both assumptions may have an effect on the estimated U_c with both analysis methods. It is therefore recommended to study the validity of:

- the assumption of zero suction pressure. In Eq. 3 and Eq. 4 the suction pressure in the topsoil is assumed negligible. When performing a GPT the soil is, when compared to a wave overtopping situation, less saturated. Van der Meijden (2024) did not find a clear relation between the measured saturation levels of the soil and the maximum tensile force. For now there is no proof to change the assumption of zero suction pressure.
- the value for the relative turbulence intensity r_0. The value used for r_0 in Eq. 3 and Eq. 4 is assumed to be realistic for high flow velocities. Insight in the structure of turbulence above a (damaged) grass cover during wave overtopping may lead to new insights regarding the real value and may explain the differences between the U_c found with the GPT and tests with the WOS.

CONCLUSIONS

Grass sod pulling tests can be used to estimate the critical flow velocity U_c for grass covers. The original equation used for this estimation is derived from results with the prototype of the device used for grass sod pulling tests. Compared to the U_c found with wave overtopping tests, the used empirical equation often underestimates U_c. Therefore, an in-depth analysis of the results of grass sod pulling tests with both the prototype and updated version of the grass sod pulling device was carried out within the project Future Dikes. This analysis has led to an adjustment of the original analysis method used to estimate the U_c. The U_c was again determined using this adjusted analysis method for all grass sod pulling tests with the updated device. A comparison of the U_c estimated with the original and adjusted analysis method shows that the U_c estimated with the adjusted analysis method corresponds better with the U_c resulting from the wave overtopping tests, especially if the grass cover did not fail during tests with the WOS. However, for grass covers that did fail the original analysis method performs better. It is currently unclear why the U_c estimated with the adjusted analysis method corresponds less with the results of the wave overtopping tests in which the grass sod did fail. It is recommended to look at this in more detail in further research. For now it is recommended to use the results of both analysis methods next to each other when estimating the strength of a grass cover.

Note that the GPT only provide an estimation of the possible erosion resistance of the grass cover on dikes and wave overtopping tests are still necessary to determine the real strength of the grass cover.

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