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OVERFLOWING TESTS ON THE ROSTOCK DREDGDIKES RESEARCH DIKE

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Abstract. As a part of the South Baltic Program, within the project DredgDikes large scale overflowing experiments on landside slopes of the Rostock research dike were carried out in September 2013. The aim of these experiments was to determine the landside slopes resistance against erosion caused by water. The test setup was in accordance with ASTM D-6460, modified to meet the project requirements, and the method used in the US NTPEP testing programme for rolled erosion control products. Therefore, three parallel flumes with a width of 0.6 m have been installed on the landside slopes at each cross-section of the research dike. Both short-term and long-term tests were carried out. Within the shot-term experiments generally five stages of discharge were realized for 45 minutes each, with erosion measurements between each stage. Each "long-term experiment" had a duration of at least 6 hours and was performed using a medium-high discharge. This paper presents the test methods as well as first results and conclusions of the experiments. The most important findings are that overflowing experiments are feasible with the proposed test set-up. Furthermore, it can be shown that under the project and test given boundary conditions the erosion resistance of the landside slopes is given.

Keywords: vegetated dike slopes, inner dike slopes, slope erosion stability, large-scale overflowing tests, flume experiments, short-term overflowing tests, long-term overflowing tests

1. Introduction

In the project DredgDikes the usability of fine-grained dredged materials for dike construction is investigated. One focus of the research lies on the erosion resistance of these materials. The stability against erosion on landside slopes is essential for the entire stability of a dike (EAK 2002/2007, EurOtop 2007). Therefore large-scale overflowing experiments on the landside slopes of the Rostock research dike were carried out in September 2013. The aim of these experiments was to determine the resistance of the vegetated slopes against both critical hydraulic parameters like discharge depth, flow velocity or shear stress and the influence of flow duration. The objective of this paper is to present the test procedure and to discuss first results of the experiments.

2. Preparation and scientific background

Erosion is the detachment, the transport and the sedimentation of soil particles. With regard to erosion resp. to obtain a quantitative variable for describing erosion, a variety of geotechnical engineers, geologists or institutions contributed in this field (e.g. Briaud et al. 2001, Hanson and Cook 2004, ECTC 2003 and 2004, ILIT 2006, Vavrina 2010, SKZ and LWG 2011, Hoffmans 2012, Reiffsteck et al. 2012). All these approaches have in common that the amount of soil loss depends on a hydraulic load. For this consideration, first it should be irrelevant whether a certain amount of soil loss happens per unit time or area. Both the effective flow velocity and the effective shear stress are of basic relevance.

The design of the Rostock research dike including the investigation of the dredged materials, geosynthetics and measurement techniques was described by Cantré et al. (2012, 2013) and Große and Saathoff (2013). The dike cross-sections were constructed with different kinds of fine-grained dredged materials, with or without rolled erosion control products (RECP), and with two different inclinations as well. As RECP a geomat (GMA) was installed 2 cm to 5 cm beneath the surface. A selection of soil mechanical values is summarised in Table 1 to characterise the materials used. To allow for overflowing experiments on the landside slopes the eastern crest of the research dike contains lowered parts where the water can overflow if the polder is filled to extend. On the greened dike surface a standard dike seeding mixture with added legumes was used. All slope surfaces had good vegetation cover ratios of approximately 80 % during the tests.

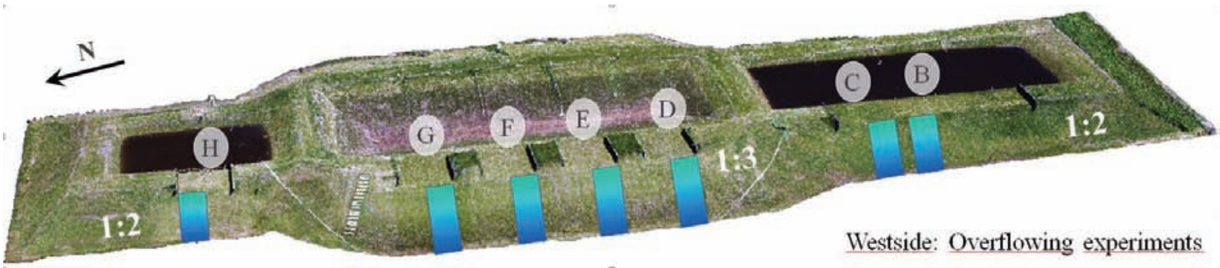


Fig. 1. Rostock research dike, West view, B-H different cross-sections for overflowing experiments

Table 1. Selected geotechnical properties (Große and Saathoff 2013)

	M1	*M2*	*M3*
Clay [%]	*25-28*	*13-17*	*15*
Sand [%]	*29-34*	*55-64*	*54*
Organic matter [%]	*10-11*	*9-10*	*6*
Lime content [%]	*9-10*	*8*	*10*

M1: Organic silt ripened for 5 yrs; M2: Organic silt ripened for 2 yrs; M3: Sandy silt, slightly organic.

Table 2. Compilation of information about the cross-sections used for overflowing tests on Rostock research dike

X-Section	*B*	*C*	*D*	*E*	*F*	*G*	*H*
Material	*2*	*2*	*2*	*2*	*1*	*1*	*3*
RECP	*no*	*yes*	*no*	*yes*	*yes*	*no*	*no*
Slope (V:H)	*1:2*	*1:2*	*1:3*	*1:3*	*1:3*	*1:3*	*1:2*
Length [m]	*6.0*	*6.0*	*7.8*	*7.8*	*7.8*	*7.8*	*5.4*
Sections(1)	*10*	*10*	*13*	*13*	*13*	*13*	*9*

(1) Number of test-section resp. measuring areas into each flume is divided by length

Fig. 1 schematically illustrates the research dike including all areas relevant for the overflowing experiments. A compilation of information about the sections used for the overflowing tests is given in Table 2.

The Rostock experiments have been planned resembling a test series in the frame of the US National Transportation Product Evaluation Program (NTPEP 2013). Within this programme, a variety of erosion control products have been tested focussing on maximum acceptable shear stresses and flow rates. Background for the overflowing experiments in the NTPEP is the standard ASTM D-6460 (2008). As basic set-up of the NTPEP experiments three parallel flumes with a length of 40 ft. (~ 12.2 m) and a width of 2 ft. (~ 0.6 m) each are installed on a slope. For the flow and erosion measurements a 20 ft. (~ 6.1 m) long section in the middle of each flume is considered. The flume inclination is 10 % for unvegetated and 20 % for vegetated samples respectively.

The advantage of this set-up is that three parallel test series can be performed simultaneously and that a very high discharge can be realised with reasonable pumping equipment by using just one of the flumes. Each single test is carried out with four levels of discharge with at least one critical discharge to reach the critical amount of soil loss of 0.5 in. (~ 1.27 cm) averaged over the entire flume area. The 20 ft. test section is separated in 10 sections. Before and after each flow event, the relative height of the soil surface is measured in each section and a cumulative soil loss index is determined for each flume. All data is recorded and then analysed focusing on the determination of a critical flow velocity and a critical shear stress.

3. Overflowing experiments on the Rostock research dike

3.1 Test set-up and measurement techniques

Based on the NTPEP test set-up three parallel flume channels have been installed on each of the DredgDikes research dike slopes. Fig. 2 shows the basic experimental set-up. Each flume has an inner width of 0.6 m. Depending on the slope inclination a specific length and number of test sections was determined (see Table 2). The flumes are made out of single walls and each of these is fixed with steel profiles and construction foam into the slope surface. Additional stability is reached with horizontal slats on the top of the walls connecting the three flumes. These wooden slats also serve as markings for the single test sections.

Fig. 2. Basic experimental set-up, cross-section H

Fig. 3. Two pumps deliver water into the polders

Fig. 4. Filled polder 3, cross-section H

Fig. 5. Closed sluice gates at cross-section H

Fig. 6. Runoff channel to lead the water back to the basin

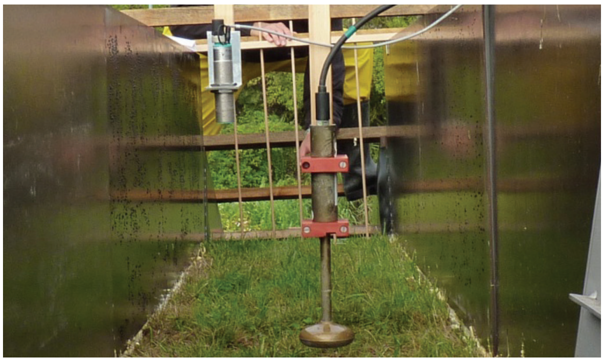


Fig. 7. Ultrasonic sensor to measure runoff depth (left), magnetic-inductive sensor to measure flow velocity (right)

On the dike crest the water inlets and the permanent instrumentation for discharge control are placed. The water delivery system includes a basin, two pumps (Fig. 3), pipes, the dike polders (Fig. 4), sluice gates (Fig. 5) and a large runoff channel (Fig. 6).

Fig. 8. Pin profiler to measure the soil loss/ gain and the discharge depth

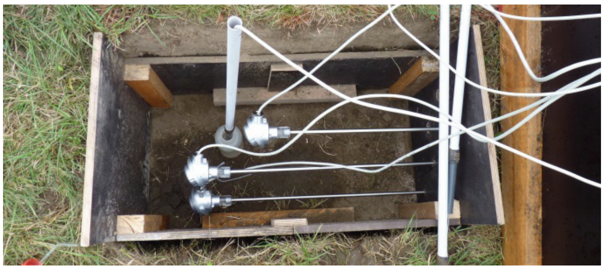


Fig. 9. TDR-sensors and tensiometers under the flumes

The discharge for the overflowing experiments can be regulated on the dike crest with sluice gates. Depending on the polder filling height and the opening width of the gate a flume target discharge can be adjusted. For peak discharges each pump delivers 300 to 350 m^3h^{-1}.

Both the flow velocity and runoff depth are determined during the experiments. To measure the flow velocity a permanently installed magnetic-inductive sensors is used on the dike crest (Fig. 7) while and a mobile inductive sensor is used on the slopes. The runoff depth is measured using ultrasonic sensors on the dike crest (Fig. 7) and with a pin-profiler on the slopes (Fig. 8).

The erosion on the slope surface is determined with the same pin-profiler (Fig. 8). For this, the relative height of the slope soil surface is measured before and after each flow event. The difference between both values indicates the amount of soil loss resp. soil gain. Therefore, the soil surface height is measured at five points in each test section orthogonal to the flow direction.

Photos of each test section were made before and after each test stage which have been used to compare the slope surface conditions, e.g. the vegetation coverage (Neumann & Henneberg 2014).

In addition the moisture content resp. the water saturation of the top layer material was determined with TDR-sensors and tensiometers in a depth of 10 and 20 cm below the outer two flumes (Fig. 9).

Fig. 10. Experimental procedure cross-section H, first discharge stage ($q \approx 0.05\ m^3(m \cdot s)^{-1}$, $v \approx 1.57\ ms^{-1}$, $\tau \approx 270$ Pa), measurment of flow velocity in the left flume

3.2 Test procedure and analysis

All experiments are carried out according to the same procedure (Fig. 10):

- Prepare the flumes including installation of measuring equipment,
- Record the initial state of the dike embankment including pin-profiling and both photographic and written documentation,
- Slowly open the sluice gates to increase the discharge to the target discharge within approximately five minutes to minimise the shock load of the soil surface and vegetation,
- Overflow for 45 minutes with the target discharge,
- Measure the flow velocity and discharge depth in every test section of each flume during the test,
- Close the sluice gates and drain the residual water,
- Record the final state of the dike embankment including pin-profiling and both photographic and written documentation (= initial recording for the next flow level or final recording for the whole test series),
- Transfer all measured data to a test record sheet.

The “long-term overflowing tests” have been performed in a similar way, expect that just one of three flumes was used and during a six hour overflowing event the amount of erosion was recorded after two and four hours (short interruptions). The long-term tests were carried out in only one of the channels of each cross section.

The target discharges had to be chosen before the start of the test series. The limiting factors are the performance of the pumps and the sizes of both the polder and the reservoir basin. Table 3 contains a compilation of the mean discharge rates and the dependent variables measured and computed in September 2013.

After finishing the field experiments the test record sheets have to be analysed. Therefore the following values have to be calculated or recalculated to control the target values:

Table 3: Mean unit discharges (q), measured and computed hydraulic values (flow velocity (v), discharge depth (h), shear stress (τ)) on the dike embankment, September 2013

	Ø q [$m^3s^{-1}m^{-1}$]	**Ø v** [ms^{-1}]	**Ø h** [m]	**Ø τ** [Pa]
Stage 1	*0.060*	*1.75*	*0.053*	*210*
Stage 2	*0.080*	*2.26*	*0.060*	*240*
Stage 3 / long-term	*0.120*	*2.62*	*0.071*	*260*
Stage 4 / 5 / long-term	*0.200*	*3.28*	*0.095*	*340*

- Soil loss resp. soil gain per test-section and cumulated for the whole flume,
- Discharge (Q) resp. unit discharge (q),
- Shear stress (τ), and
- Flume roughness (k_{St}).

The main objective of the analyses of the obtained data is to determine a relationship between measured soil loss (= erosion) and effective hydraulic loads (= effective flow velocity, v_{eff} and effective shear stress, τ_{eff}). Another objective is to find a critical value for the hydraulic parameters (v_{crit}, τ_{crit}) which leads to a certain amount of average soil loss – e.g. 1.27 cm as recommended in ASTM D 6460 (2008).

First, the values of the shear stresses (τ) which occur in each test section have to be calculated using equation (1)

$$\tau = \rho_W \cdot g \cdot h \cdot I \qquad (1)$$

with: τ = shear stress on the soil surface, ρ_w = mass density of water (1000 kgm^{-3}), g = acceleration of gravity, h = discharge depth, and I = slope inclination.

Then the control values for the discharge are calculated using the continuity law (2) and the Torricelli sluice equation (3)

$$Q = A \cdot v \qquad (2)$$

$$Q = \mu \cdot a \cdot b \cdot \sqrt{2 \cdot g \cdot h_0} \qquad (3)$$

with: Q = discharge, A = flow area, v = flow velocity, μ = discharge coefficient for sluices, a = sluice opening width, b = flume width, g = acceleration of gravity, h_0 = impounding depth in front of the sluice.

The next calculation steps are based on the ASTM standard D-6460 (2008) and are used to determine the amount of soil loss. For this, the topology of every test section before an overflowing event is set off against the topology after an overflowing event and the soil loss (SL) is computed using equation (4). Following this, the average resp. cumulative soil loss (CSL) in the entire flume is determined using equation (5).

$$SL = \frac{(SSF_i - SSF_{erod}) \cdot A_T}{A_W} \tag{4}$$

$$CSL = \frac{\sum_{1...n} SL}{n} \tag{5}$$

with: SL = soil loss in a test-section, SSF_i = initial soil surface, SSF_{erod} = eroded soil surface, A_T = test-section area, A_W = wetted area of a test-section, CSL = cumulative soil loss of the whole flume, n = number of test-sections.

Finally, the development of the channel roughness (k_{St}) during each test series is computed using the Gauckler-Manning-Strickler equation (6).

$$k_{St} = \frac{v}{r_{hy}^{2/3} \cdot I^{1/2}} \tag{6}$$

with: k_{St} = Manning-Strickler roughness, v = flow velocity, r_{hy} = hydraulic radius, I = slope inclination.

3.3 Typical results and evaluation

On the whole, 25 test series on 7 dike cross-sections with a total of 83 single overflowing tests were carried out in September 2013, including 79 short-term and 4 long-term tests. Due to the large amount of data, only typical results will be presented here. The following tables show the final results of all short-term (Table 4) and long-term (Table 5) overflowing experiments on each cross-section.

From each series of tests on the single dike cross-sections, the soil loss rates were compared with the flow velocities resp. the shear stresses. Fig. 11 gives examples of the measured amounts of soil loss versus calculated shear stresses. The results show, that on cross-section E the highest measured amount of soil loss occurred. In cross-section F a different dredged material was installed while all other boundary conditions are the same as in E. Here, only a medium amount of soil loss occurred. Similar results were obtained at cross-sections B and D.

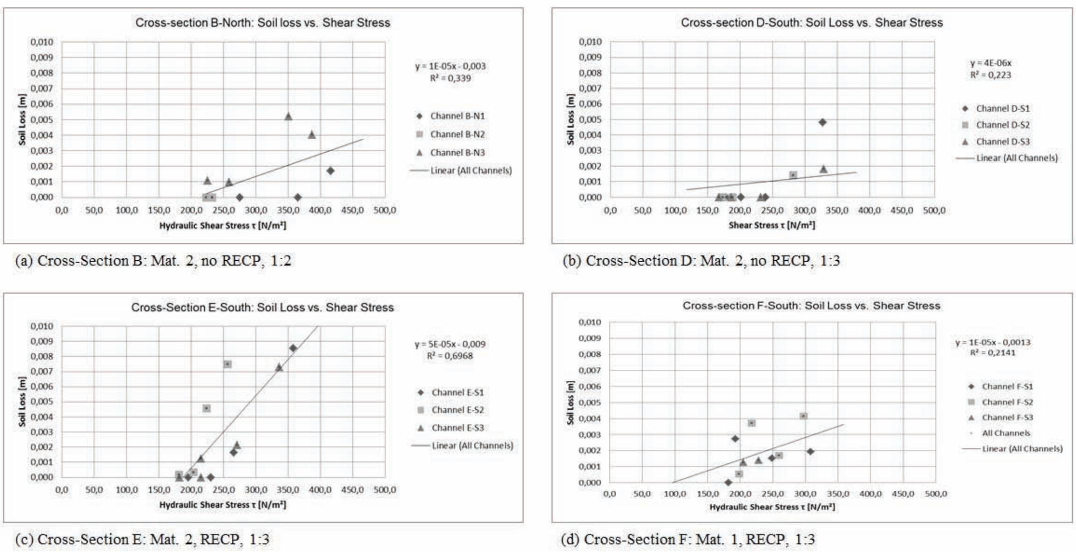
Fig. 11 (c+d) show initial shear stresses around 200 Pa for cross-sections E and F with material M2 resp. M1, with and without installed RECP and a slope inclination of 1:3. In comparison, Fig. 11 (a+b) show

Table 4. Summary of maximum cumulative soil loss (CSL) and maximum hydraulic forces of each cross-section and short-term test series

	Max. Ø CSL *[m]*	***Max. Ø q*** *[m³s⁻¹m⁻¹]*	***Max. Ø v*** *[ms⁻¹]*	***Max. Ø h*** *[m]*	***Max. Ø τ*** *[Pa]*
B	*0.005*	*0.180*	*3.47*	*0.085*	*416*
C	*0*	*0.228*	*3.79*	*0.095*	*464*
D	*0.005*	*0.279*	*3.66*	*0.101*	*329*
E	*0.009*	*0.235*	*3.61*	*0.110*	*358*
F	*0.004*	*0.253*	*3.58*	*0.094*	*308*
G	*0*	*0.194*	*3.46*	*0.095*	*311*
H	*0.002*	*0.270*	*3.48*	*0.124*	*606*

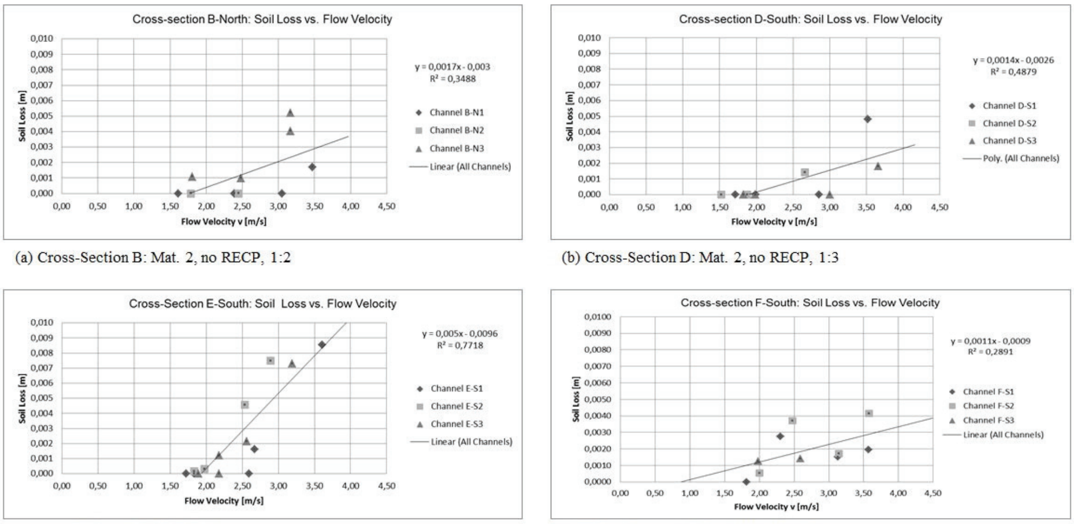
Table 5. Summary of maximum cumulative soil loss (CSL) and maximum hydraulic forces of each cross-section and long-term test series

	Max. CSL *[m]*	***Ø q*** *[m³s⁻¹m⁻¹]*	***Ø v*** *[ms⁻¹]*	***Ø h*** *[m]*	***Ø τ*** *[Pa]*
C	*0*	*0.190*	*3.12*	*0.070*	*349*
D	*0.005*	*0.226*	*2.80*	*0.081*	*264*
E	*0.012*	*0.129*	*2.83*	*0.076*	*248*
H	*0*	*0.214*	*2.97*	*0.070*	*344*



(a) Cross-Section B: Mat. 2, no RECP, 1:2
(b) Cross-Section D: Mat. 2, no RECP, 1:3
(c) Cross-Section E: Mat. 2, RECP, 1:3
(d) Cross-Section F: Mat. 1, RECP, 1:3

Fig. 11. Examples of cumulated soil loss versus shear stress, cross-sections B (1:2) and D, E, F (1:3)



(a) Cross-Section B: Mat. 2, no RECP, 1:2 (b) Cross-Section D: Mat. 2, no RECP, 1:3

(c) Cross-Section E: Mat. 2, RECP, 1:3 (d) Cross-Section F: Mat. 1, RECP, 1:3

Fig. 12. Examples of cumulated soil loss versus flow velocity, cross-sections B (1:2) and D, E, F (1:3)

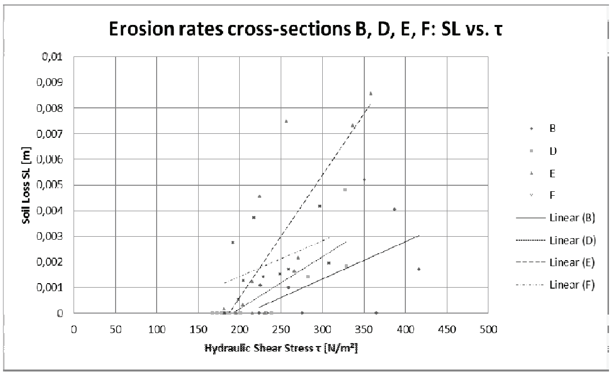


Fig. 13. Erosion rates in cross-sections B, D, E, F; regarding soil loss and shear stress, the steeper the trend line the higher the erosion rate

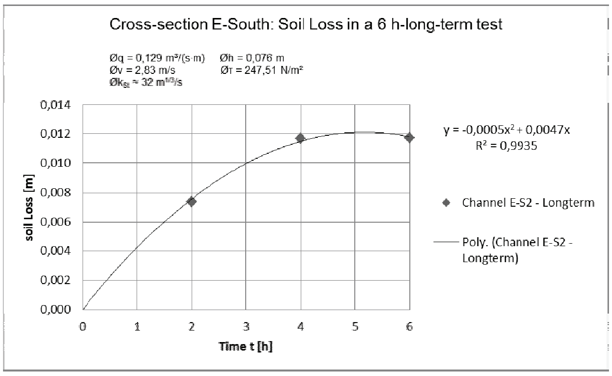


Fig. 14. Soil loss on cross-section E - long-term test

the results for cross-sections B and D but without installed RECP, and different slope inclinations of 1:3 (D) resp. 1:2 (B), where the initial shear stresses start around 250 Pa. However, contrary to the experiments on cross-sections F, E and B only three cases have occurred at cross-section D, where soil loss could be measured. The situation is similar with the initial flow velocities (Fig. 12): at cross-sections F, E, and D the start of erosion was determined to 2.0 ms^{-1} while for cross-section B an average value of approximately v = 2.5 ms^{-1} was determined.

All test results have in common that only very low values of cumulated soil loss were determined. None of the results is in the range of critical soil loss of 1.27 cm as recommended in the ASTM D 6460 (2008) standard (see Table 4 and Figs. 11 and 12). The comparably high values of soil loss in cross-section E can be explained by increased erosion in the lower test-sections of the flumes, where certain amounts of soil and vegetation eroded (slid) on top of the installed RECP.

Due to the relatively broad distribution of the measurement results, it was not possible to define a “best fit” trend line through the data points. Therefore a linear trend line was chosen to define the soil loss function. The slopes of the trend lines describe the magnitude of the erosion rates (relationship between soil loss and hydraulic loads): the steeper the trend line, the higher is the erosion rate. Again, the results in cross-section E show the highest erosion rate (Fig. 13).

Fig. 14 shows the result of a long-term test at cross-section E. The results were analysed by plotting the amount of soil loss over the time. Fig. 14 shows that after four hours overflowing no further change of soil loss occurred. Similar results show the long-term tests at the other cross-sections but with a lower amount of soil loss: no soil loss at cross-sections C and H, and just 5 mm at cross-section D (compare Table 5).

Regarding the soil water saturation, no later than 15 minutes – one third of the first discharge stage – all measurements show full saturation down to a depth of at least 20 cm.

4. Discussion

With respect to all boundary conditions – properties of the used dredged materials and geosynthetics, slope inclination, vegetation, and discharge values – no major erosion failure was caused by the overflowing tests performed on the Rostock research dike.

Considering the single cross-sections and their construction, cross-section E with a slope inclination of 1:3, and an installed erosion control product has the biggest amount of cumulated soil loss (*CSL* = 0.009 m) after the short-term tests. However, even this value is very small. Possible reasons for the larger erosion on E may be insufficient compaction of the soil surface, a lower interlocking between soil particles and RECP, or a weak connection between plant roots and RECP, among others. The other cross-sections showed *CSL*-values between 0.005 m and 0.000 m.

Regarding the long-term experiments also cross-section E showed the biggest amount of cumulated soil loss (*CSL* = 0,012 m), while the other cross-sections showed mean *CSL*-values between 0.005 m (D) and 0.000 m (C and H) after six hours of overflowing. Again, the aforementioned reasons apply, explaining the larger soil loss value for cross-section E.

However, it should be noted that all results of the soil loss values are averages of the individual test sections in each flume. For example, on cross-section E a maximum soil loss (*SL*) of 2.0 cm to 2.4 cm occurred in at least six of the seven lower test sections of the single flumes. Considering the long-term tests in this cross-section, soil loss between 2.1 cm and 2.9 cm occurred in the test-sections seven to ten.

As yet no recommendations for a critical amount of soil loss on a slope regarding overflowing events exist, except in the ASTM standard D-6460 (2008). All measured amounts of soil loss of the first DredgDikes overflowing tests are far below the critical values recommended in the ASTM standard (critical *CSL* = 1.27 cm), although the overflowing discharge of approximately 200 $ls^{-1}m^{-1}$ is far bigger than the design discharges e.g. given in EurOtop (2007). At least four discharge levels are needed to get closer to the critical values of shear stress or flow velocity and the dependent value of critical soil loss step by step. In order to exceed a critical value of soil loss, a much higher pump performance (> 1,400 mh^{-1}) will be necessary which will be considered in follow-up experiments.

There were also difficulties in determining the various hydraulic parameters such as the discharge depth on the dike slope. The determination of the discharge depth in long laminar conditions is generally unproblematic. However, in the test conditions on the dike slopes the flow conditions were highly turbulent. Then it is difficult to decide where the exact water level is and how it can be measured accurately. Technical aids such as ultrasonic sensors usually fail here. The measurement of the flow velocity is equally problematic (Fig. 15) when it comes to finding the exact point to measure the mean flow velocity. The accuracy of the measurements of discharge depth and flow velocity, however, is basis for the subsequent computations of effective shear stress and the determination of the critical flow parameters.

Fig. 15. Flow velocity measurement, turbulent conditions with a lot of air entrainment

5. Conclusions

The overflowing experiments on the Rostock research dike in September 2013 were carried out to determine the landside slope resistance against erosion caused by water. The resistance against erosion is defined by critical values of shear stress and flow velocity and a dependent value of a certain amount of soil loss. The advantages of the test set-up on the Rostock research dike are that the dike-specific erosion resistance resp. erodibility can be determined, and that several site-specific boundary conditions can be considered (construction material, additives, geosynthetics, slope inclination, discharge and discharge depth, flow velocity, among others).

1. As yet no officially critical value regarding the amount of soil loss for landside dike slopes exists in the literature.
2. On the whole with rising hydraulic forces (q, v, and τ) an increased amount of soil loss could be measured.
3. With respect to the ASTM D 6460 (2008) standard no critical amount of soil loss was measured at the DredgDikes overflowing experiments in September 2013. On single cross-sections no soil loss could be measured at a maximum flow velocity of $v = 3.79\ ms^{-1}$ and a maximum shear stress of $\tau = 464\ Nm^{-2}$ (maximum unit discharge of $q = 228\ ls^{-1}m^{-1}$). The maximum measured soil loss of $CSL = 0.009$ m occurred at $v = 3.61\ ms^{-1}$ resp. $\tau = 358\ Nm^{-2}$ ($q = 235\ ls^{-1}m^{-1}$).
4. Within the DredgDikes overflowing experiments in September 2013 it could not be shown that beneath the surface installed erosion control products reduce erosion. The highest amount of soil loss occurred at a cross-section with installed RECP. Causes may be an insufficient compaction of the soil surface, a low interlocking between soil particles and RECP, or a weak connection between plant roots and RECP.
5. Weaknesses of the September 2013 experiments: (i) the maximum performance of the pumps was too low for finding critical hydraulic parameters, (ii) measurements just in the beginning of every test-section in the flumes avoid accurate data collection between two slats, (iii) regarding erosion, there was no focus on the dike toe, (iv) measurement of the accurate discharge depth and the mean

flow velocity, (v) just four flumes were used for long-time experiments.

6. The second test series is following in May 2014. To determine critical hydraulic parameter the discharge has to be at least $Q \approx 1.400\ m^3h^{-1}$ resp. $q \approx 650\ ls^{-1}m^{-1}$ with an overflowing depth of approximately $h = 0.15$ m and an average flow velocity of approximately $v = 4\ ms^{-1}$.

Nomenclature

A	= vertical flow area, $[m^2]$
A_T	= Test-section area, $[m^2]$
A_w	= Wetted area of a test-section, $[m^2]$
a	= Sluice opening width, [m]
b	= Flume width, [m]
CSL	= Cumulated soil loss in a flume, [m]
g	= Acceleration of gravity, $[ms^{-2}]$
h	= Discharge depth, [m]
h_0	= Impounding depth in front of the sluice, [m]
I	= Slope inclination, [-]
k_{St}	= Manning-Strickler roughness, $[m^{1/3}s^{-1}]$
μ	= Discharge coefficient for sluices, [-]
n	= Number of test-sections, [-]
Q	= Discharge, $[m^3h^{-1}]$, $[m^3s^{-1}]$ or $[ls^{-1}]$
q	= Unit discharge, $[m^3s^{-1}m^{-1}]$ or $[ls^{-1}m^{-1}]$
ρ_W	= Mass density of water, $[kgm^{-3}]$
r_{hy}	= hydraulic radius, [m]
SL	= Soil loss in a test-section, [m]
SSF_i	= Initial soil surface, [m]
SSF_{erod}	= Eroded soil surface, [m]
τ	= Shear stress, [Pa] or $[Nm^{-2}]$
τ_{eff}	= Effective shear stress, [Pa] or $[Nm^{-2}]$
τ_{crit}	= Critical shear stress, [Pa] or $[Nm^{-2}]$
v	= Flow velocity, $[ms^{-1}]$
v_{eff}	= Effective flow velocity, $[ms^{-1}]$
v_{crit}	= Critical flow velocity, $[ms^{-1}]$

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