FLUME EXPERIMENTS TO DETERMINE THE EROSION STABILITY OF THE GERMAN DREDGDIKES RESEARCH DIKE

Jan Olschewski[1], Stefan Cantré[2], Fokke Saathoff [3]

[1, 2, 3] Universität Rostock, Chair of Geotechnics and Coastal Engineering, Justus-von-Liebig-Weg 6, D-18059 Rostock,
[1] jan.olschewski@uni-rostock.de, [2] stefan.cantre@uni-rostock.de, [3] fokke.saathoff@uni-rostock.de

Abstract. In the German part of the project DredgDikes fine-grained dredged materials are analysed as replacement for standard dike cover materials. In the course of this the erosion stability of the ripened dredged materials with and without vegetation is a critical factor which has been tested in a variety of laboratory and field experiments. Therefore a laboratory flume was used for initial bench-scale tests, and large-scale field flume tests have been performed at the Rostock research dike to show the erosion stability of the actual construction. The bench-scale flume experiments were conducted in the laboratories of the Chair of Geotechnics and Coastal Engineering, University of Rostock. The laboratory flume has a length of 2.75 m and a width of 0.25 m with an inclination of 1:3. Different samples of dredged materials were built into the flume: (i) unvegetated, (ii) unvegetated with erosion control product, (iii) vegetated, and (iv) vegetated with erosion control product. The instrumentation compounds an ultrasonic sensor to determine the water depth and a flow sensor for the velocity. To determine the amount of soil loss/gain at the sample surface different methods were used: (i) laser scanning, (ii) optical recording by hand, and (iii) pin profiling. Before and after each single experiment the sample surface was surveyed. The large-scale field experiments were performed on the DredgDikes research dike in Rostock/ Markgrafenheide. The test dike is made of three different dredged materials, constructed with different slope inclinations, and surfaces with and without the use of erosion control products. The test setup was in accordance with ASTM D-6460 -modified to meet the project requirements- and the method used in the US American NTPEP testing program for rolled erosion control products. Therefore, three parallel flumes with a width of 0.6 m each were installed on the landside slopes of each cross-section of the research dike. The instrumentation compounds ultrasonic sensors to determine the water depth on the dike crest and a magnetic inductive sensor for the velocity. To determine the amount of soil loss/gain and the water depth on the slope a pin profiler was used. Both short-term and long-term tests were carried out. The state of the dike surface was determined before and after each experiment. The objective of this paper is to discuss the results of the 2013 field experiments with regard to the lab experiments.

Keywords: laboratory overflowing experiments, 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 both small-scale flume experiments (e.g. Lesch 2012) and large-scale overflowing experiments on the landside slopes of the Rostock research dike (Olschewski et al. 2014) were carried out between May 2012 and September 2013. The aim of these experiments was to determine the resistance of dredged materials and 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 procedures 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, van der Meer et al. 2006, 2007, 2010, 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.

In preparation for the large-scale overflowing field experiments on the Rostock research dike, small-scaled tests were carried out in the laboratories of the Chair of Geotechnics and Coastal Engineering. For this a laboratory flume was designed and constructed ~~by Lesch (2012)~~(Fig. 1). Aim of the laboratory experiments was to preselect a suitable dredged material with the highest resistance against erosion, and to find resp. test different methods for measuring erosion of unvegetated and vegetated soils. The laboratory flume was developed with reference to boundary conditions of the Rostock research dike. Thus, a slope of 1:3 was used for all experiments, which could also be varied. Furthermore four different dredged materials were used as samples for the experiments, three of these materials (material M1 - M3) were also used for the research dike. Vegetated and unvegetated samples were prepared, both with and without erosion control geomat (GMA) installed approximately 2 cm beneath the soil surface. A selection of soil mechanical values is summarised in Table 1 to characterise the used materials.

Fig.~~.~~ 1~~:~~. Laboratory flume, sample boxes in the front, Chair of Geotechnics and Coastal Engineering

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.

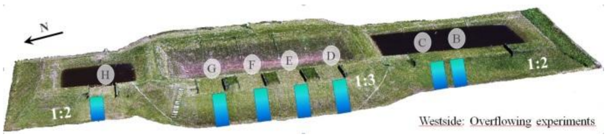


Fig. 2. Rostock research dike, West view, B-H different cross-sections for overflowing experiments

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

Cantré et al. (2012, 2013) and Große and Saathoff (2013) already described the design of the Rostock research dike including the investigation of the dredged materials, geosynthetics and measurement techniques. The dike cross-sections were constructed with different kinds of fine-grained dredged materials (Table 1), with or without rolled erosion control products (RECP), and with two different inclinations as well. As RECP a GMA is installed 2 cm to 5 cm beneath the surface. 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. 2 schematically illustrates the research dike including all areas relevant for the overflowing experiments and Table 2 gives a compilation of information about the sections used for the overflowing experiments.

Both the small-scale and the large-scale experiments in Rostock have been planned resembling the US standard ASTM D-6460 (2008) and a test series in the frame of the US National Transportation Product Evaluation Program (NTPEP 2013) – both modified to meet the DredgDikes project specific requirements. 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.

This set-up allows to perform three parallel test series simultaneously and to realise a very high discharge 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.

Regarding the overflowing experiments in the project DredgDikes, the main objective of the analyses of all 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)

$$\tau = \rho_W \cdot g \cdot h \cdot I \tag{1}$$

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 for the large-scale field experiments (3)

$$Q = A \cdot v \tag{2}$$

$$Q = \mu \cdot a \cdot b \cdot \sqrt{2 \cdot g \cdot h_0} \tag{3}$$

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)

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

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

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.

For describing the nature of the flow conditions (supercritical or subcritical resp. laminar or turbulent) the Froude number (Fr) resp. the Reynolds number (Re) have to be calculated with equations (7) and (8).

$$Fr = \frac{v}{\sqrt{g \cdot h}} \tag{7}$$

$$\mathrm{Re} = \frac{\rho_W \cdot v \cdot r_{hy}}{\eta} \tag{8}$$

with v = flow velocity, g = acceleration of gravity, h = discharge depth, ρ_W = mass density of water, r_{hy} = hydraulic radius, η = dynamic viscosity at water temperature T = 288.15 K.

3. Small-scale laboratory flume experiments

3.1 Test set[SC1]-up and measurement techniques

The basic structure of the construction consists of a turbulence tank and the actual flume. It has a width of 0.27 m and an effective length of 2.75 m with a slope of 1:3. The water delivery system includes a basin, a pump, a pipe and the turbulence tank (Fig. 1, Fig. 4). The discharge can be regulated with a slide valve in the pipes. The maximum possible discharge is about 95 m^{3}h^{-1} resp. 380 m^{3}h^{-1}m^{-1} (26 ls^{-1} resp. 106 ls^{-1}m^{-1}).

For determining the soil loss for the whole sample with a pin profiler, the flume is separated lengthwise in circa ten test sections, each with a size of 0.27 m × 0.27 m.

The flow velocity is measured at several points of the flume with a propeller flow meter. The discharge depth is determined with an ultrasonic sensor at the top of the flume and measured with a scale resp. a pin profiler at each flume test section. The soil surface is measured before and after each flow event, for determining the amount of soil loss. Different methods were tested in the course of the test series: (i) determining the surface geometry with a laser scanner, (ii) optical recording of the soil surface by hand and with photos, and (iii) recording of the soil surface with a pin-profiler.

3.2 Test procedure and analysis

Regardless of the way of determining the amount of soil loss, the test procedure is always the same. After installing a soil sample (Fig. 3), the initial soil surface geometry has to be measured with one of the mentioned methods (laser scanning, optical recording by hand, pin-profiling). Then the first level of overflowing starts including measuring the discharge depth and flow velocity. Between two overflowing levels and after the last one the soil surface geometry has to be measured again.

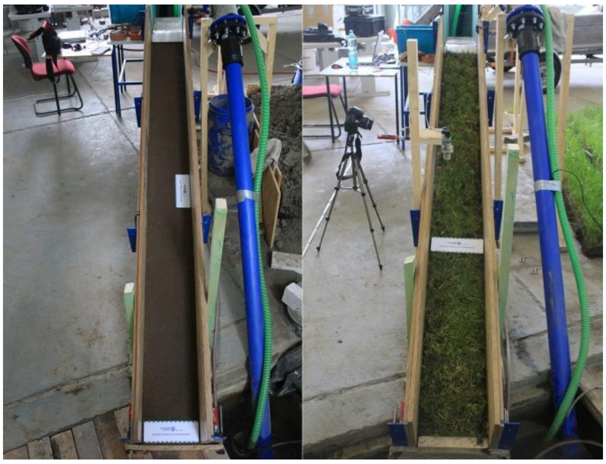


Fig. 3. Installed soil samples, unvegetaded (left) and unvegetated (right)

Before and after each flow event the soil surface has to be scanned for generate 3D-models of the sample to determine the amount of soil loss with the laser scanning method. The first scan is the reference scan. With the following scans the soil loss can be calculated by computing the difference volume. The basic experimental set-up is shown in Fig. 4. For describing the amount of soil loss the erosion rate E is defined:

$$E = \frac{V_E}{W} \tag{9}$$

with V_E = eroded soil volume, W = volume of water.

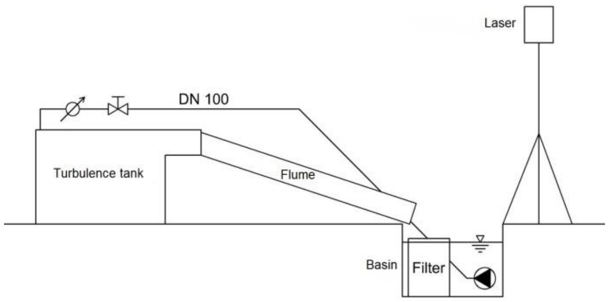


Fig. 4. Basic experimental set-up with laser scanner (Lesch 2012)

The optical recording by hand is quite similar to the laser scan method. Except for that the whole soil sample surface (vegetated or unvegetated) has to be measured out and recorded by hand, with scales and photos. Disadvantage of this method is, that no reliable values for erosion rates or soil loss resp. soil gain can be given.

For determining the amount of erosion with a pin-profiler, the relative height of the slope soil surface is measured in each test section at three points orthogonal to the flow direction before and after each flow event. The difference between both values indicates the amount of soil loss resp. soil gain.

Depending on whether unvegetated or vegetated samples are tested, the minimum discharge has to be chosen. The following tables show the mean minimum and maximum discharge rates and the dependent variables for unvegetated (Table 3) and vegetated samples (Table 4).

Table 3. Mean unit discharges (q) for unvegetated samples, measured and computed hydraulic values (flow velocity (v), discharge depth (h), shear stress (τ)), Froude and Reynolds numbers on the dike embankment

	Ø q *[ls⁻¹m⁻¹]*	**Ø v** *[ms⁻¹]*	**Ø h** *[m]*	**Ø τ** *[Pa]*	**Fr**⁽¹⁾ *[-]*	**Re**⁽²⁾ *[-]*
Lowest	*0.3*	*-(3)*	*-(3)*	*-(3)*	*-(3)*	*-(3)*
Highest	*26*	*1.4*	*0.024*	*80*	*2.89*	*19932*

(1) $Fr < 1$: subcritical, $Fr > 1$: supercritical
(2) $Re \leq 2320$: laminar, $Re \geq 2320$: turbulent
(3) immeasurable / incomputable

Table 4. Mean unit discharges (q) for vegetated samples, measured and computed hydraulic values (flow velocity (v), discharge depth (h), shear stress (τ)), Froude and Reynolds numbers on the dike embankment

	Ø q *[ls⁻¹m⁻¹]*	**Ø v** *[ms⁻¹]*	**Ø h** *[m]*	**Ø τ** *[Pa]*	**Fr**⁽¹⁾ *[-]*	**Re**⁽²⁾ *[-]*
Lowest	*0.65*	*0.07*	*0.01*	*32.7*	*0.22*	*392*
Highest	*106*	*2.8*	*0.06*	*200*	*3.65*	*83804*

(1) $Fr < 1$: subcritical, $Fr > 1$: supercritical
(2) $Re \leq 2320$: laminar, $Re \geq 2320$: turbulent

After finishing each laboratory test series the test record sheets have to be analysed including the calculation of the effective discharges (*Q* resp. *q*, see formula 2), the shear stress (τ, see formula 1), and the soil loss resp. soil gain per test-section (*SL*, see formula 4) and cumulated for the whole flume (*CSL*, see formula 5). The flow conditions are supercritical

3.3 Typical results and evaluation

In total so far, 44 test series with a total of 127 single overflowing tests were carried out between May 2012 and October 2013. Due to the large amount of data, only typical results will be presented here.

For unvegetated soil samples the laser scanning method works very well. Fig. 5 shows two laser scans for example: one after 5 minutes and one after 15 minutes (material M3). With the measured soil loss volume, the erosion rates could be calculated for the different dredged materials and for a marsh clay as reference. Fig. 6 shows the erosion rates for the tested unvegetated soils.

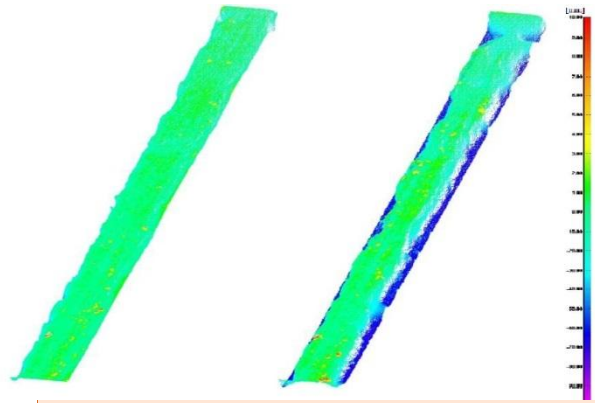


Fig. 5. Laser scan after overflowing events on material M3, after 5 minutes (left), after 15 minutes (right), dark blue = -70 mm soil loss, green = +/-0 mm soil loss/gain, red = +10 mm soil gain, Ø soil loss ≈ 18,5 mm (q ≈ 3,2 $ls^{-1}m^{-1}$, v ≈ 0.22 ms^{-1}, τ ≈ 10 Pa)[JO2]

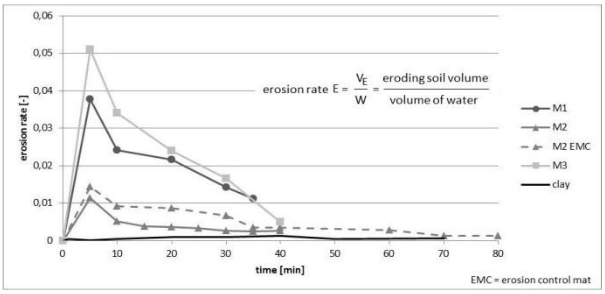


Fig. 6. Erosion rates of dredged materials (M1-M3) and clay (Cantré et al. 2013)

Within the laboratory flume experiments among the dredged materials material M2 - with and without GMA) - shows results with the best erosion stability. M1 and M3 have up to five times higher erosion rates. In contrast, the lowest erosion rate showed the conventional dike cover material (marsh clay).

The pin-profiler was used exclusively for vegetated samples. Due to the quite low pump performance no significant erosion was observed in almost non experiment. In the course of installation some cracks occurred crosswise in length direction. Only in these areas a significant amount of soil eroded downstream (Fig. 7).

The following chart (Fig. 8) shows the soil loss versus the hydraulic shear stress.

Fig. 7. Downstream erosion above the geomat (GMA), originate at a crosswise crack (M2, December 2013)

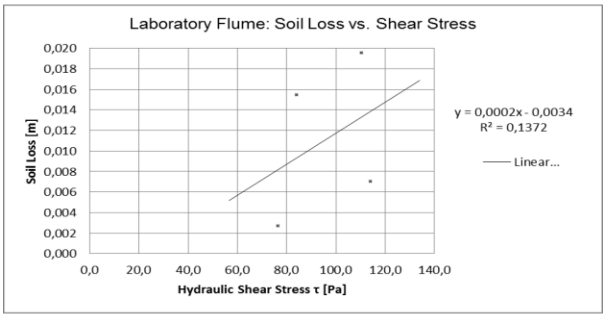


Fig. 8. Cumulated soil loss versus shear stress, only significant case of erosion in the course of laboratory flume tests with vegetated samples (M2, December 2013)

Fig. 8 shows an initial shear stress between 60 Pa and 80 Pa and a mean maximum soil loss of *CSL* ≈ 0.019 m. The mean hydraulic parameters were Ø q ≈ 64 $ls^{-1}m^{-1}$, Ø v ≈ 2,37 ms^{-1}, Ø τ ≈ 110 Pa.

4. Large-scale field experiments

Olschewski, Cantré & Saathoff (2014) already described the large-scale field tests including test set-up, test procedure and results. For the sake of completeness here these main facts will be summarized.

4.1 Test set-up and measurement techniques

The field test set-up is based on the NTPEP tests: three parallel flumes have been installed on each cross-section of the research dike. Fig. 9 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 (Fig. 9). The flumes are made out of single walls fixed with steel profiles and construction foam into the slope surface. Horizontal slats on the top of the walls connecting the three flumes and additional stability is reached. These wooden slats also serve as markings for the single test sections.

The water inlets and the permanent instrumentation for discharge control are placed on the dike crest. The water delivery system includes a basin, two pumps, pipes, the dike polders (Fig. 2), sluice gates (Fig. 10) and a runoff channel (Fig. 11).

Fig. 9: Basic experimental set-up and procedure, cross-section H, first discharge stage ($q \approx 50$ $ls^{-1}m^{-1}$, $v \approx 1.57$ ms^{-1}, $\tau \approx 270$ Pa), measurment of flow velocity in the left flume, 6^{th} test section

Fig. 10: Closed sluice gates at cross-section H

Fig. 11: Runoff channel to lead the water back to the basin

The sluice gates regulate the discharge rates on the dike crest. Depending on the polder filling height and the opening width of a gate the flume target discharge can be adjusted. For peak discharges each of the two pumps delivered 300 m^3h^{-1} to 350 m^3h^{-1}.

The flow velocity and the runoff depth are determined during the single experiments. To measure the flow velocity a permanently installed magnetic-inductive sensors is used on the dike crest (Fig. 13) while and a mobile inductive sensor is used on the slopes. The runoff depth is measured using ultrasonic sensors on the dike crest (Fig. 13) and with a pin-profiler on the slopes (Fig. 12).

The erosion on the slope surface is determined with the same pin-profiler. 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.

Fig. 12: Pin profiler to measure the soil loss/ gain and the discharge depth

Fig. 13: Ultrasonic sensor to measure runoff depth (left), magnetic-inductive sensor to measure flow velocity (right)

Furthermore, 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 flumes.

4.2 Test procedure and analysis

Each experiment is carried out according to the same procedure:

- preparation of flumes and measuring equipment,
- record the initial state of the embankment (pin-profiling, photographic and written documentation),
- slowly increase the discharge by opening the sluice gates within approximately five minutes, to minimise the shock load of the soil surface and vegetation,
- 45 minutes overflow with the target discharge,
- measure the flow velocity and discharge depth in every test section of each flume (Fig. 9),
- 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 subsequent flow level or final recording for the whole test series),
- transfer of 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 of each cross section was used and during six hours overflowing the amount of erosion was recorded after two and four hours (short interruptions).

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 5 contains a compilation of the mean discharge rates and the dependent variables measured and computed in September 2013.

Table~~.~~ 5~~:~~. Mean unit discharges (q), measured and computed hydraulic values (flow velocity (v), discharge depth (h), shear stress (τ)), Froude and Reynolds numbers on the dike embankment, September 2013, Stages 3-5 = long-term

	Ø q [$ls^{-1}m^{-1}$]	*Ø v* [ms^{-1}]	*Ø h* [m]	*Ø τ* [Pa]	*Fr*(1) [-]	*Re*(2) [-]
Stage 1	60	1.75	0.053	210	2.43	69203
Stage 2	80	2.26	0.060	240	2.95	99208
Stage 3	120	2.62	0.071	260	3.14	132061
Stage 4 / 5	200	3.28	0.095	340	3.40	207773

(1) $Fr < 1$: subcritical, $Fr > 1$: supercritical
(2) $Re \leq 2320$: laminar, $Re \geq 2320$: turbulent

The test record sheets have to be analysed after finishing the field experiments. Therefore several values have to be calculated or recalculated to control the target values: (i) soil loss per test-section and cumulated for the whole flume, (ii) discharge, (iii) shear stress, and (iv) the flume roughness.

4.3 Typical results and evaluation

25 large-scale field 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 6) and long-term (
Table 7) overflowing experiments on each cross-section.

The soil loss rates were compared with the shear stresses (Fig. 14) resp. the flow velocities (Fig. 15) from each series of tests. The results show, that on cross-section E the highest measured amount of soil loss occurred on material M2. In cross-section F ~~a different dredged material was~~where the only difference is the installed material M1~~ 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.

Table~~.~~ 6~~:~~. 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* [$ls^{-1}m^{-1}$]	*Max. Ø v* [ms^{-1}]	*Max. Ø h* [m]	*Max. Ø τ* [Pa]
B	0.005	180	3.47	0,085	416
C	0	228	3.79	0.095	464
D	0.005	279	3.66	0.101	329
E	0.009	235	3.61	0.110	358
F	0.004	253	3.58	0.094	308
G	0	194	3.46	0.095	311
H	0.002	270	3.48	0.124	606

Table~~.~~ 7~~:~~. Summary of maximum cumulative soil loss (*CSL*) and maximum hydraulic forces (unit discharge (q), flow velocity (v), discharge depth (h), shear stress (τ)) of each cross-section and long-term test series

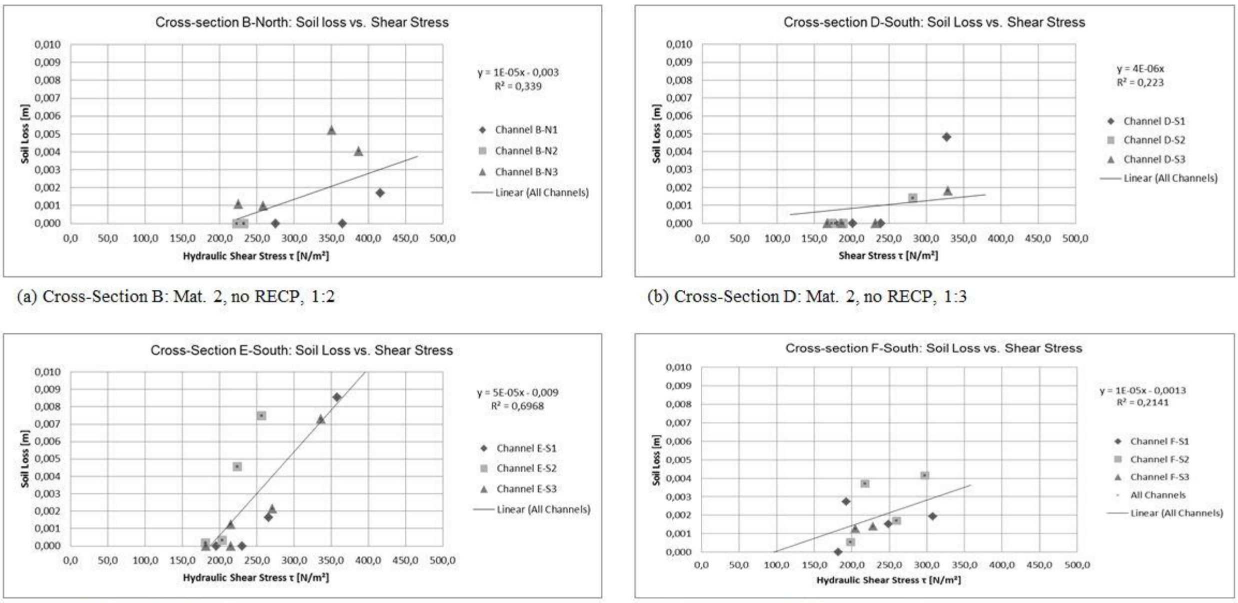
	Max. CSL [m]	*Ø q* [$m^3s^{-1}m^{-1}$]	*Ø v* [ms^{-1}]	*Ø h* [m]	*Ø τ* [Pa]
C	0	190	3.12	0.070	349
D	0.005	226	2.80	0.081	264
E	0.012	129	2.83	0.076	248
H	0	214	2.97	0.070	344

Fig. 14 (c) and (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. 14 (a) and (b) show 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 in three of eleven single tests at cross-section D, soil loss could be measured. The situation is similar with the initial flow velocities (Fig. 15): at cross-sections F, E, and D the initial erosion was determined ~~to~~ at 2.0 ms^{-1} while for cross-section B a mean value of approximately v = 2[SC3].5 ms^{-1} was determined. These flow velocities are not the values of the critical velocity regarding a *CSL* of 1.27 cm.

In the whole only very low values of cumulated soil loss were determined in the experiments. 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 (compare Table 6 and Fig. 14 and Fig. 15). The four measured 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 for all charts to define the cross-section specific soil loss functions. 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. 16).

Fig. 17 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. 17 shows that after four hours of overflowing no further change of soil loss occurred. Similar results ~~show~~ were derived in the long-term tests ~~at~~ on the other ~~cross-~~sections but with a lower amount of soil loss: no soil loss ~~at~~ on~~cross-~~ sections C and H, and ~~just~~ only 5 mm ~~at~~ on ~~cross-~~ section D (compare Table 7).



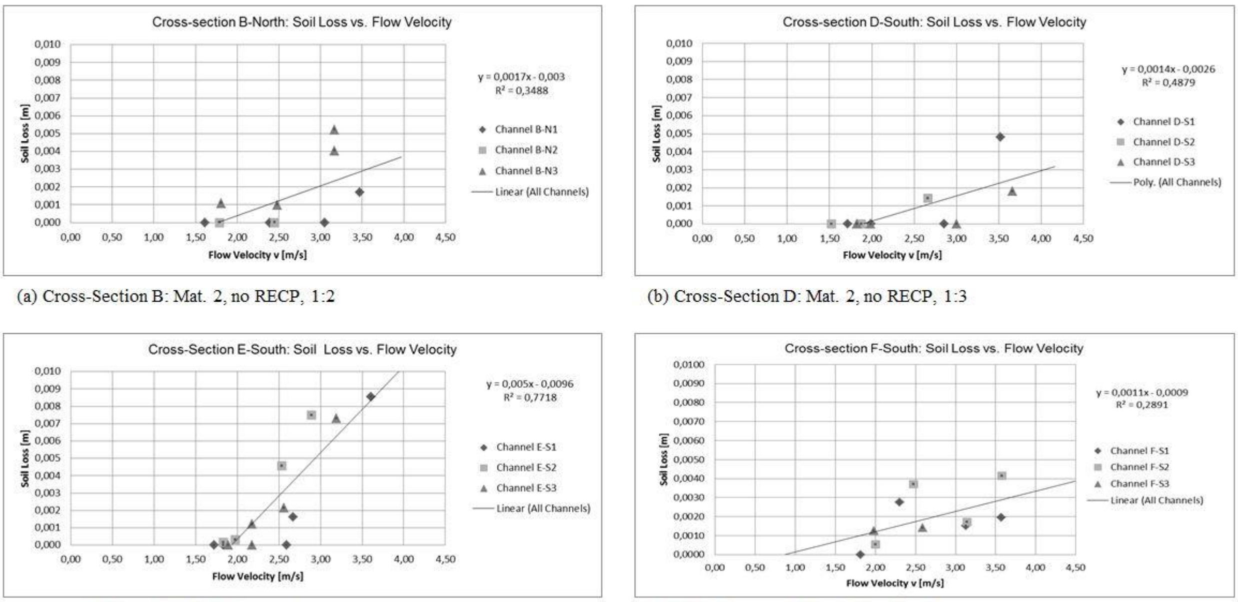
(a) Cross-Section B: Mat. 2, no RECP, 1:2

(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.~~,~~ 14.~~:~~ Examples of cumulated soil loss versus shear stress, cross-sections B (1:2) and D, E, F (1:3)



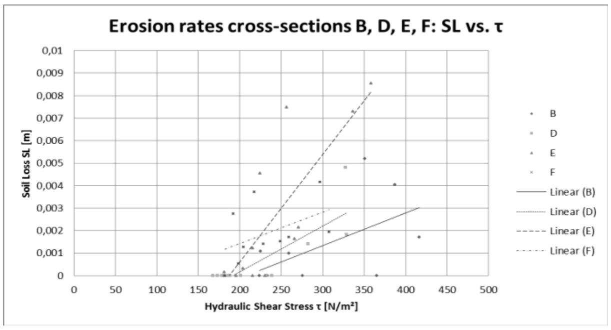
(a) Cross-Section B: Mat. 2, no RECP, 1:2

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

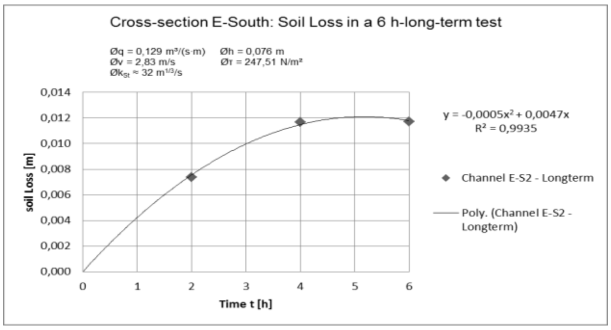
(c) Cross-Section E: Mat. 2, RECP, 1:3

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

Fig.~~,~~ 15~~:~~. Examples of cumulated soil loss versus flow velocity, cross-sections B (1:2) and D, E, F (1:3)



Fig~~.~~ 16~~:~~. 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~~.~~ 17~~:~~. Soil loss on cross-section E - long-term test

The moisture and suction pressure measurements underneath the overflow surface showed that after maximum ~~Regarding the soil water saturation, no later than~~ 15 minutes - one third of the first discharge stage - ~~all measurements show full~~the soil was fully saturated~~ion~~ down to a depth of at least 20 cm.

5. Discussion ~~and conclusions~~

~~5.1 Discussion~~

The erosion stability of the dredged materials investigated in the laboratory flume show up to five times lower erosion stability compared to ~~With respect to the stability against erosion the comparison between the dredged materials used in the project and~~ the marsh clay ~~–~~which is conventionally used for dike top layers at the North Sea. ~~– shows that at least in the laboratory tests the dredged materials have a up to five times lower erosion stability.~~ However,~~But~~ these results ~~just~~ only count for unvegetated samples. All ~~used~~ vegetated samples tested showed a ~~much better~~comparable performance regarding erosion stability: no erosion could be measured up to the maximum~~a~~ unit discharge of $q \approx 106$ ls^{-1}m^{-1} ($v \approx 2.8$ ms^{-1}, $\tau \approx 200$ Pa). Due to installation failures in the form of cracks ~~crosswise~~ perpendicular to the ~~length~~ flume axis~~direction~~ erosion occurred above the installed geomat in particular cases. ~~In the whole~~Overall, material M2 showed the best performance among the dredged materials in the course of the laboratory flume experiments.

The possible reasons for the results of the large-scale field experiments have ~~been~~ already been discussed in~~(~~ Olschewski et al. 2014~~)~~. In the course of the large-scale field experiments and with respect to all boundary conditions of the Rostock research dike – ~~(~~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.

Cross-section E with a slope inclination of 1:3~~,~~ and an installed erosion control product ~~has~~ showed the ~~biggest~~ largest amount of cumulated soil loss (*CSL* = 0.009 m) after the short-term tests. However, even this value is ~~quite~~ comparably low. Possible reasons for the larger erosion on section E may be explained by insufficient compaction of the soil surface on top of the RECP, a lower interlocking between soil particles and RECP, or a weak connection between plant roots and RECP, among others. All other cross-sections showed ~~after the experiments~~ *CSL*-values between 0.005 m and 0.000 m after the experiments.

~~Regarding~~ Also in the long-term experiments ~~also cross~~-section E showed the ~~biggest~~ largest 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, i~~It should be noted, however, 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~~ there are 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 (≥ 1400 m^{3}h^{-1}) will be necessary which will be considered in follow-up experiments.

Furthermore, within the future it has to be discussed, whether the definition of soil loss (*SL* resp. *CSL*) is an adequate definition for describing the damage or failure of the slope resp. of the grass cover. It has to be considered whether special categories for describing the conditions of grass covers have to be established, e.g. initial damage, various damage locations, failure and non-failure after testing (Van der Meer 2010).

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 with a lot of air entrainment (Fig. 18). 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 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.

It should be noted that the overflowing experiments not serve as a substitute for overtopping experiments, where due to the waves other hydraulic loads are mobilized on the slope.

Fig~~.~~ 18.~~:~~ Turbulent water surface, a lot of air entrainment in the lower area of the slope resp. flume

6~~5.2~~ Conclusions

The overflowing experiments in the small-scale laboratory flume and on the Rostock large-scale research dike between were carried out to determine the landside slope resistance resp. the stability of dredged materials 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 at both small-scale laboratory flume experiments and large-scale field experiments.
3. In the course of the laboratory flume experiments dredged material M2 showed the best performance (unvegetated) with respect to the stability against erosion. In the course of field experiments no significant difference between M1, M2, or M3 could be determined.
4. In the course of the small-scale laboratory flume experiments no major erosion failure occurred ~~at~~ on vegetated soil samples.
5. With respect to the ASTM D 6460 (2008) standard no critical amount of soil loss was measured ~~at~~ in the DredgDikes overflowing experiments. On ~~single~~ some cross-sections no soil loss could be measured at a maximum flow velocity of $v = 3.79\ \mathrm{ms^{-1}}$ and a maximum shear stress of $\tau = 464\ \mathrm{Nm^{-2}}$ (maximum unit discharge of $q = 228\ \mathrm{ls^{-1}m^{-1}}$). The maximum measured soil loss of $CSL = 0.009$ m occurred at $v = 3.61\ \mathrm{ms^{-1}}$ resp. $\tau = 358\ \mathrm{Nm^{-2}}$ ($q = 235\ \mathrm{ls^{-1}m^{-1}}$).
6. It could not be shown that erosion control products installed beneath the surface ~~installed erosion control products~~ reduce surface 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~~on top of the RECP, a low interlocking between soil particles and RECP, or a weak connection between plant roots and RECP.
7. Weaknesses of the small-scale laboratory flume experiments: (i) Major sample damages installation ~~failures~~ can occur easily during installation, ~~which distort~~distorting the results significantly, (ii) the maximum pump performance ~~is~~ chosen for the tests was too low ~~for~~ to find~~ing~~ critical hydraulic parameters.
8. Weaknesses of the large-scale field experiments: (i) the maximum performance of the pumps was too low ~~for~~ to find~~ing~~ critical hydraulic parameters, (ii) measuring of soil loss/gain in each test-section in five points on one line orthogonal to the flow direction avoids accurate data collection, (iii) regarding erosion, there was no focus on the dike toe, (iv) measurement of ~~the~~ an accurate discharge depth and ~~the~~ mean flow velocity is complicated, (v) ~~just~~ only four flumes were used for long-term~~ime~~ experiments.

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]
E = Erosion rate [-]
Fr = Froude number, [-]
g = Acceleration of gravity, [ms^{-2}]
h = Discharge depth, [m]
h_0 = Impounding depth in front of the sluice, [m]
η = Dynamic viscosity, [Pa·s] or [$kgm^{-1}s^{-1}$]
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}]
Re = Reynolds number, [-]
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]
T = Temperature, [K]
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}]
V_E = Eroded soil volume [m^3]
W = Volume of water [m^3]

References

ASTM D 6460: Standard Test Method for Determination of Rolled Erosion Control Product (RECP) Performance in Protecting Earthen Channels from Stormwater-Induced Erosion. ASTM International. West Conshohocken, 2008. 9 p.

Briaud, JL.; Ting, FCK.; Chen, HC.; Cao, Y.; Han SW.; Kwak KW. 2001. Erosion Function Apparatus for Scour Rate Predictions, *Journal of Geotechnical and Geoenvironmental Engineering* 127(2): 105-113.

Cantré, S.; Saathoff, F.; Große, AK.; Nitschke, E. 2012. Dredged Materials in Dike Construction - First Results of the DredgDikes Large-Scale Field Tests in Rostock, *12th Baltic Sea Geotechnical Conference*, 281-285.

Cantré, S.; Große, AK.; Neumann, R.; Nitschke, E.; Henneberg, M.; Saathoff, F. 2013. Fine-grained organic dredged materials for dike cover layers - Material characterisation and experimental results, *XX World Dredging Congress and Exibition*, 14 p.

EAK 2002/2007. *Empfehlungen für die Ausführung von Küstenschutzwerken durch den Ausschuss für Küstenschutzwerke der Deutschen Gesellschaft für Geotechnik e.V. und der Hafenbautechnischen Gesellschaft e.V.* [German recommendations for the design of coastal protection constructions], Westholsteinsche Verlagsanstalt Boyens & Co., Heide i. Holstein, 589 p.

ECTC Test Method 2: Standard Index Test Method fort the Determination of Unvegetated Rolled Erosion Control Product (RECP) Ability to Protect Soil From Rain Splash and Associated Runoff Under Bench-Scale Conditions. Erosion Control Technology Council. St. Paul, 2003. 10 p.

ECTC Test Method 3: Standard Test Method for Determination of Unvegetated Rolled Erosion Control Product (RECP) Ability to Protect Soil from Hydraulically-Induced Shear Stresses Under Bench-Scale Conditions. Erosion Control Technology Council. St. Paul, 2004. 9 p.

EurOtop 2007. *Wave Overtopping of Sea Defences and Related Structures: Assessment Manual*, Boyens Medien GmbH & Co. KG, Heide i. Holstein, 178 p.

Große, AK.; Saathoff, F. 2013. Soil mechanical aspects in characterizing fine grained organic dredged material from the Baltic Sea area, *GeSed Conference*, 8 p.

Hanson, GJ.; Cook, KR. 2004. Apparatus, Test Procedures, and Analytical Methods to Measure Soil Erodibility In Situ, *Applied Engineering in Agriculture* 20(4): 455-462.

Hoffmans, GJCM. 2012. *The Influence of Turbulence on Soil Erosion*, Eburon Academic Publishers, Delft, 2012, 260 p.

ILIT 2006. Investigation of the Performance of the New Orleans Flood Protection Systems in Hurricane Katrina on August 29, 2005 - Overtopping Induced Erosion Studies. [cited Jan 23 2014] Available online: <http://www.ce.berkeley.edu/projects/neworleans/>

Lesch, S. 2012. *Projekt DredgDikes – Ermittlung der Erosionsstabilität gegen Überströmen von begrüntem Baggergut in einer kleinmaßstäblichen Strömungsrinne*. M.Sc. thesis, Rostock: Universität Rostock, 134 p.

Neumann, R.; Henneberg, M. 2014. The Project DredgDikes: Characterization of chemical properties of the dredged material and first results on vegetation monitoring. *South Baltic Conference on Dredged Materials in Dike Construction*, 8 p.

NTPEP 2013. National Transportation Product Evaluation Program - Erosion Control products (ECP), Reports. [cited Jan 23 2014] Available online: <http://www.ntpep.org/Pages/ECP.aspx>

Olschewski, J.; Cantré, S.; Saathoff, F. 2014. Overflowing tests on the Rostock DredgDikes research dike, *South Baltic Conference on Dredged Materials in Dike Construction*, 8 p.

Reiffsteck, P.; Haghighi, I.; Chevalier, C. 2012. Erodibility diagnostic of existing hydraulic earthworks by Mobile Jets Erosion Test, *6th International Conference on Scour and Erosion*, 8 p.

SKZ/LWG 20011. *Schlussbericht – Erarbeitung und Verifizierung von Auswahlkriterien für geosynthetische Erosionsschutzsysteme der AiF-Forschungsvereinigung Fördergemeinschaft für das Süddeutsche Kunststoff-Zentrum e.V.* [Final report – Development and verification of eligibility criteria for geosynthetic erosion control systems], German Plastics Center (SKZ), Würzburg, 160 p.

Van der Meer, JK.; Bernardini, P.; Snijders, W.; Regeling, E. 2006. The wave overtopping simulator, *30th International Conference on Coastal Engineering*, 13 p.

Van der Meer, JW.; Bernardini, P.; Steendam, GJ.; Akkerman, GJ.; Hoffmans, GJCM. 2007. The wave overtopping simulator in action, *Coastal Structures 2007 Proceedings of the 5th International Conference*, 645-656.

Van der Meer, JW.; Hardeman, B.; Steendam, GJ.; Schttrumpf, H.; Verheij H. 2010. Flow depths and velocities at crest and inner slope of a dike, in theory and with the Wave Overtopping Simulator, *30th International Conference on Coastal Engineering*, 15 p.

Vavrina, L. 2010. *Ansatz zur Bewertung der Schutzfunktion bewachsener Deichbinnenböschungen*. Ph.D. thesis, Essen: Universität Duisburg-Essen, 146 p.