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The erosion resistance of different dryed fine-grained dredged materials for application in dike construction

La resistance d'erosion des materiaux de dragage en application pour des constructions de digues

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ABSTRACT: Since 10 years different dryed (ripened) fine-grained dredged materials rich in organic matter have been investigated at the University of Rostock regarding their application as construction materials for sea dikes. For a dike cover material erosion resistance is one of the most important characteristics. Therefore, a variety of laboratory and field tests have been performed to learn more about the materials' resistance against surface and internal erosion. In this paper selected results of laboratory flume tests, disintegration tests, and hole erosion tests (HET) with bare (unvegetated) soil samples are presented and the results are compared. While the data of lab flume and disintegration tests lead to a rather medium erosion stability of the ripened dredged materials, the internal erosion stability seems to be extremely high according to the HET. This is particularly interesting in the context of a very high erosion resistance of the materials with grass cover (tested in large-scale flume tests) and the issues of shrinkage cracking and animal bore holes.

RÉSUMÉ: Depuis 10 ans, l'Université de Rostock a étudié différents matériaux de dragage séchés à grain fin et organiques, pour leur utilisation comme matériaux de construction de digues. Pour un revêtement de digue, la résistance à l'érosion est le plus importante. Par conséquent, divers essais en laboratoire et sur le terrain ont été réalisés pour en apprendre sur la résistance des matériaux à l'érosion de surface et à l'érosion interne. Dans cet article, des résultats sélectionnés d'essais dans les canaux de laboratoire, d'essais de désintégration et d'essais d'érosion (HET) avec des spécimens de sol sans végétation sont présentés et les résultats sont comparés. Les données des essais en canal laboratoire et des essais de désintégration résultat à une stabilité à l'érosion moyenne des matériaux de dragage, tandis que la stabilité à l'érosion interne semble extrêmement élevée selon le HET. Les materiaux herbeux ont une très grande résistance à l'érosion (testés dans des canaux d'écoulement de grande échelle) bien que des problèmes de fissuration et des trous des animaux.

Keywords: erosion resistance; dredged material; dike construction; hole erosion test; disintegration test

1 INTRODUCTION

Flood protection dikes are usually protected by cover material that resists the hydraulic forces to prevent erosion. The erosion processes most relevant for dike stability are surface erosion caused by wave run-up, overflowing/ overtopping and maximum impact pressures as well as internal erosion, such as piping, contact erosion, concentrated leak erosion or suffosion.

When alternative construction materials are planned to replace standard materials, they should usually possess similar characteristics and functionality. For over a decade now, the chair of Geotechnics and Coastal Engineering at the

University of Rostock has investigated fine-grained dredged materials (DMs) from harbour and channel maintenance dredging for their application as dike cover materials, particularly on sea dikes at the Baltic Sea coast, resulting in a first edition of a handbook on the use of DMs in dike construction (Saathoff et al. 2015).

Baltic Sea dikes are usually built of a stable sand core covered by a cohesive soil (usually glacial marl or clay) and a vegetation layer. Therefore, the erosion resistance of the cover material is an important issue. Although the main factor for erosion protection on a greened soil cover is the vegetation, the soil material itself needs to be erosion resistant, too; particularly regarding damages in the vegetation, cracks or animal bore holes and internal erosion processes.

The standard dike cover materials are becoming increasingly scarce, particularly because they often need to be mined in environmentally sensitive areas. As an alternative, dewatered dredged sediments with appropriate geotechnical characterisation can be suitable replacement materials, particularly when they provide good erosion resistance and turf development. Fine grained dredged sediments are widely available, particularly in coastal areas, due to the necessary maintenance works in harbours and navigation channels. Experience shows, that some of the materials are well suited for dike construction.

The erosion resistance of different DMs from the Baltic Sea area has been investigated in the laboratory using disintegration and aggregate stability tests, hole and jet erosion tests as well as a laboratory flume. While most of the tests were performed in Rostock, the first set of hole and jet erosion tests were done at Irstea, Aix-en-Provence. In the field, large-scale flume experiments were performed (Cantré et al. 2017) and the seepage water flow was observed, with particular respect to bore-holes after intensive vole activity and to desiccation cracks. Based on current laboratory tests on internal erosion, large-scale field tests are in preparation to investigate piping phenomena. In the present paper, the results of the hole erosion, disintegration, and lab flume tests are discussed.

Table 1. Selected geotechnical properties

2 MATERIALS AND METHODS

2.1 Soil materials

The soil materials under consideration are dewatered dredged materials (DMs) to be used as alternative dike cover materials. During the investigations in the frame of the DredgDikes EU project and its national predecessors, a variety of DMs were analysed for their potential applicability in dike construction. In Denmark, DM samples from six locations were taken (Koge, Mosede and Tars Harbours; Vordingborg, Gronsund and Sandhage Channels). In Germany, DMs from four different dredging ponds were analysed (Rostock, Körkwitz, Ribnitz-Damgarten, Drigge/Rugia). Materials for comparison were taken from dike covers on the peninsula Darß/Zings, marl from the Baltic Sea coast in front of Sassnitz (island of Rugia) and marsh clay from Hamburg and Nordstrand.

From the analysed DMs, only selected samples from Rostock and Drigge/Rugia proved to be suitable for dike covers. They come from the Warnow river mouth area in Rostock, processed on the municipal processing facility and from the Drigge dredging containment facility on the island of Rugia, dredged in the vicinity of the city of Stralsund. The materials from Rostock are processed in the dredging polders and on ripening fields. The Drigge materials are usually not processed and only dry as far as possible inside the containment polders.

Five different batches of DM with differing characterisation were chosen for in depth analysis. To compare the erosion stability to standard dike materials, the marsh clay from Hamburg and the marl from Sassnitz (Rugia) were used.

Parameter	M1	M2	M3	S2	D	Marl	Marsh Clay	Clay
Clay [%] 1)	25-28	22-25	15	20-24	15-19	5	17-19	30
Sand [%] 1)	29-34	40-47	54	32-39	44-52	89	36-45	2
w [%]	61-68	55-73	46	50-60	62-76	13	21-22	
LL [%]	111	96	63	105	82-123	15	40	37
PL [%]	75	60	45	72	23-40	12	19	20
PI [%]	36	36	18	33	50-60	3	21	17
SL [%]	43-45	39-40	32-34		32-47			14
Vs [%]	41-42	40	23-27	45	10-57	7-9	30-33	
OM [%] 3)	10-11	9-10	6	7-10	5-6	2	3	3
LC [%]	9-10	8	10		2-7	12	1	18
$c_{u,r}$ [kPa]	53-132	19-34	120	25-50	5-31 2)	21-27	80-87	
φ [°]	28-30	28-31	30		24-29			28
c [kPa]	35-47	13-19	59		7-15			23
k_f [m/s] 4)	$4\text{-}6 \cdot 10^{-8}$	$7\text{-}9 \cdot 10^{-10}$	$2\text{-}10 \cdot 10^{-9}$	$2\text{-}70 \cdot 10^{-9}$	$4\text{-}70 \cdot 10^{-10}$	$1 \cdot 10^{-7}$	$1 \cdot 10^{-10}$	
w_{opt} [%]	40-43	32-35	31	40-45	24-32	9	14	17
OD [g/cm³]	1.2	1.3	1.4	1.2	1.3-1.4	2.1	1.8	1.7

1) DIN ISO 11277 ; 2) c_{fv}; 4) calculated from TOC, 4) lab values differ from field values by 10-1000
LL/PL/SL Atterberg limits; PI plasticity index; V_s volumetric shrinkage ratio; OM organic matter content; LC lime content; $c_{u,r}$ rem. undrained shear strength, φ/c shear parameters, k_f hydr. conductivity, w_{opt} opt. water content; OD Proctor density

In Table 1 a selection of characteristic geotechnical values is presented.

In addition to the Table 1 values, the erosion resistance was estimated using the critical critical shear stress τ_c estimation method for cohesive soils according to Smerdon and Beasley (1959) using the plasticity index PI as main influencing factor. The DMs were estimated to erode with applied loads $\tau_c \approx 1...3$ N/m².

2.2 Investigation methods

2.2.1 Laboratory flume tests

For an initial investigation on erosion stability of the DMs, a small scaled flume was used with samples of 0.25 x 2.75 m² flat area and a soil thickness of 0.07 m. The samples were prepared in wooden frames, in which they were compacted and then put into the flume where they were overtopped with tap water. Discharge, water depth and the eroded surface were recorded. For the bare soil samples, a laser scanner was used to record the initial and final states of the soil surface after each load step. The minimum possible discharge to be realised was 2.4 m³/h/m. With respect to the later installation of the materials on a 1:3 inclined slope, this inclination was also used in the experiments, leading to a minimum shear stress of 6.7 N/m², already exceeding the theoretical values after Smeardon and Beasly. For evaluation, a volumetric erosion rate was used as the quotient of the volume of runoff water and the eroded soil volume within a respective time step. 5 and 10 minute time steps were chosen for the experiments.

2.2.2 Disintegration tests

The disintegration of aggregates or compacted samples in water immersion was tested using the disintegration tests after Endell (BAW 2015) and Weißmann (2003). The general setup of a disintegration test is shown in Figure 1. The samples are put into separate wire mesh baskets which are connected to electric scales and submerged in a water basin with distilled or tap water.

In Germany, the disintegration test according to Endell is recommended (BAW 2015) to estimate the erosion susceptibility of clay in waterways construction. For the analysis at least five proctor compacted samples (diameter 0.02 m; height 0.04 m) are used. The test ends when a constant weight reading is reached after a testing time of at least 24 hrs. The analysis procedure results in the disintegration number value Z(t) as a function of time. To compare different samples the disintegration number after 8 hours Z(8) is used. A high Z(8) value identifies a low erosion resistance.

The Weißmann test was developed to analyse the erosion resistance of marsh clay covers on North Sea dikes. Compared to the Endell test the cylindrical samples are larger (0.05 m diameter/height). They are prepared in a Proctor apparatus with optimum (Proctor) water content w_{opt} for good compaction. Three test series with dry, standard (w_{opt}) and wet samples are prepared. The result value of the Weißmann test is the time t_{30} when a sample has lost 30 % of its initial weight or else when the testing time exceeds 24 hours (erosion resistant). To compare different results, the disintegration number $t_{30,V}$ is computed from the result curves of the three test series for a consistency index CI = 0.8. In the study, the Weißmann samples were also prepared at initial/natural water content for comparison.

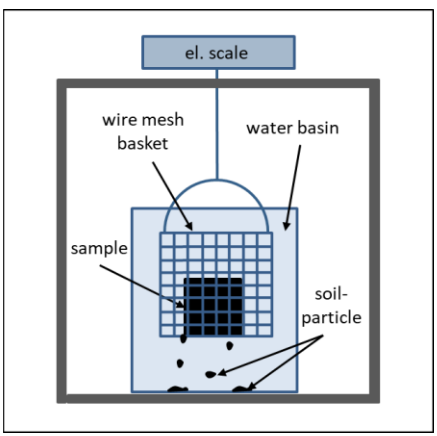

Figure 1. *Schematic of disintegration test*

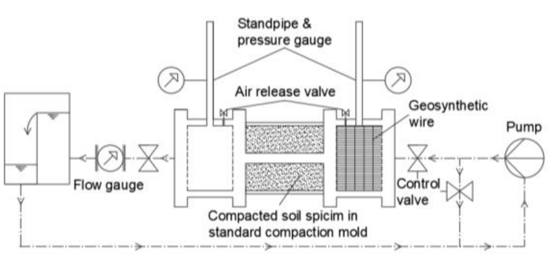

Figure 2. *Schematic of the Hole Erosion Test*

2.2.3 Hole Erosion Test (HET)

Hole erosion tests (HET) are basically similar to the pinhole test. For soils with agglomerates exceeding the diameter of the small hole of the standard pin-hole test, a larger hole is needed to prevent clogging and to allow particles to erode inside the hole. The HET accounting for this issue was first developed by Wan and Fell (2004).

Disturbed samples are prepared in the proctor apparatus using the standard proctor sample size, and undisturbed samples are usually gained with the standard 10 cm diameter core cutter. The test setup usually includes two water reservoirs in different elevations to represent the hydraulic gradient, a pipe including the soil sample, usually horizontally installed, and pressure gauges in front of and behind the soil sample to measure the actual hydraulic gradient at the sample (Figure 2).

The correlation between erosion rate ε and shear stress τ is assumed to be linear (equation 1) to describe the erosion resistance of a soil and to determine the parameters of critical shear stress τ_c, erosion coefficient C_e and erosion index I_e. I_e ranges from <2 (extremely fast erosion) to >6 (extremely slow).

$$\varepsilon = C_e(\tau - \tau_c) \tag{1}$$

$$I_e = -\log(C_e) \tag{2}$$

Where ε (kg/s/m²) is the erosion rate, C_e (s/m) is the erosion coefficient, τ (N/m²) ist the actual shear stress, τ_c (N/m²) is the critical shear stress and I_e (-) is the erosion index.

In the original HET after Wan and Fell, a hole of 6 mm diameter is pre-drilled in the centre of the sample (inital condition). Inside the hole, the water flow induced shear stress leads to an erosion progress on the pipe wall. At the end of the test, the hole diameter is measured on a paraffine cast (final condition). The progress of the hole diameter during the HET run is estimated by the current flow rate Q_i, pressure gradient ΔH_i

and a friction factor for turbulent flow ($f_{t,i}$) which is interpolated between initial and final state. Finally, τ_c is determined graphically on the shear stress- erosion rate plot extrapolating the regression function to its intersection with the τ-axis. The erosion coefficient is defined as the slope of this regression function from which the erosion index I_e (equation 2) can be computed to classify the soil into 6 groups of erosion resistance.

To estimate a suitable hydraulic head in which an erosion is expected to be initalized, a standard HET needs several repetitions with increasing hydraulic heads from 5 to 1,200 mm (Wan and Fell 2004). Already in the first test series (performed at Irstea, Aix-en-Provence), the DMs under consideration showed an erosion resistance that exceeded the measurement range of the standard test setup. Therefore, the Rostock HET setup was modified using a pump to increase the upper hydraulic head up to a level of 10 m. The tests can now be performed using a fixed hydraulic gradient (fixed upper and lower basins), with variable gradients (variable upper and fixed lower basin) and with large variable gradients (upper head applied by pump).

From the results of the flume and standard soil mechanical testing, material M2 was chosen for the HET tests. In initial studies, M2 was compared with marsh clay and clay using remolded samples. For the latest studies, undisturbed samples of M2 were produced from the DredgDikes research dike (Saathoff et al. 2015) in preparation of a large-scale erosion test in the field.

3 RESULTS AND DISCUSSION

3.1 Laboratory Flume Tests

Flume tests were performed on two samples of the materials M1, M2, M3 and marsh clay each. The degree of compaction was between 75 % and 85 % due to the high initial water contents of the materials. In the flume, the flow conditions were generally turbulent (Re > 4000) and supercritical (Fr > 1) to simulate conditions that would occur during overflowing and overtopping of dike embankments.

The bare soil samples were tested with a very low discharge (2.4 m³/h/m) for a duration of 30 minutes, applying a shear stress of 6.7 N/m² followed by another 10 minutes with a discharge of 11.6 m³/h/m. The marsh clay was tested with approximately 10 times the load.

The DMs were compared to the marsh clay regarding their erosion rate (Figure 3). In the flume tests, the erosion rate was defined as the quotient of eroded soil volume Vs and overflowing water volume Vw during a defined time step. Material M2 showes the best results among the three tested DMs, with an average of only 1.1 mm of erosion depth after 30 minutes. The critical shear stress for surface erosion of the bare DM is probably below 5 N/m² on a 1:3 slope.

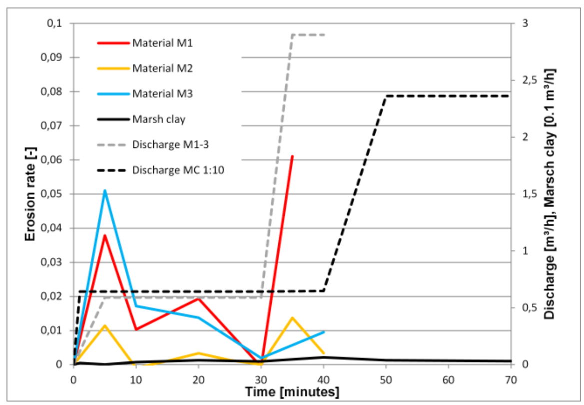

Figure 3. Erosion rates (Vw/Vs) from laboratory flume tests

3.2 Disintegration Test

Both disintegration tests showed high disintegration of most of the samples in a relatively short time in which large aggregates fell off the basket. In the Endell test, all samples started to crumble between 10 s and 1,000 s, losing 40 to 60 % of their initial weight within the first 10,000 s. Intermediately, the weight remained constant, as some of the fallen aggregates did not pass through the mesh. Towards the end of the test, the weight increased again. In contrast, samples with lower water content started to absorb water right after the beginning of the test and the weight increased to 120 %. After some time, the increase stopped and the samples showed the fastest and largest disintegration of all samples.

The disintegration numbers Z(8) are shown in Figure 4, scaled to the respective natural water content. This shows that (apart from M2 where the aggregates inside the basket gained weight due to water absorption) all materials show the lowest Z for w_n.

In the disintegration test after Weißmann, each of the curve of the three defined water contents showed similar progress. The oven dryed samples absorbed water during the full extend of the test. A weight increase up to 180 % of the initial weight was recorded, due to the saturation the samples before disintegration.

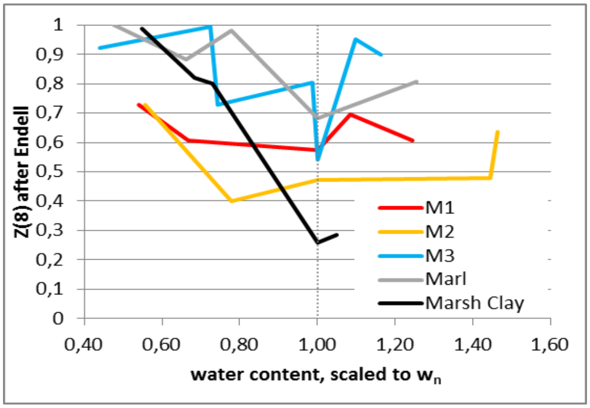

Figure 4. Disintegration numbers vs. normalised water content – justification for the use of w_n

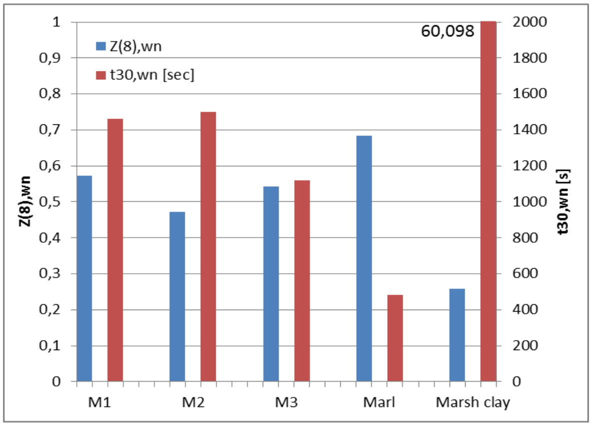

Figure 5. Disintegration numbers z(8) and times t_{30} for initial / natural water content

Only little disintegration was observed. The pre-saturated samples showed constant weight for a long time, before only a little amount of crumbling started at the end of the test procedure. Only the samples at natural water content showed a similar trend to the Endell test, where samples started to disintegrate after about 1,000 s, finally losing 60 % of their intial weight. Based on these test results, the disintegration time $t_{30,V}$ for CI = 0.8 could not be computed, and thus the disintegration time for natural water content $t_{30,wn}$ was used for comparison. Investigation of different water contents showed an increasing disintegration time (and erosion restance) with increasing water content. Among the tested DMs, M2 performed best (Figure 5). M1 and M3 show comparable results. The comparably sandy marl material showed the fastest disintegration and the marsh clay performed best among all materials.

3.3 Hole Erosion Test

As yet, five series of HET tests were performed: The initial test at Irstea with M1 and marsh clay (HET Irstea), HET R1 to compare remolded samples of M2 and clay with a constant head apparatus without in-line pressure measurement, HET R2 with undisturbed samples of M2 from section 2 of the research dike with lower compaction, HET R3 with undisturbed samples of M2 from section 1 of the research dike (better compaction), and HET R4 with R3-samples but applying an increased hydraulic load (pump).

The results for the erosion index and critical shear stress are given in Tables 2 and 3 respectively. It can be shown that the DM is at least as erosion resistant against piping erosion as the marsh clay and clay samples. Undisturbed, well compacted samples showed the highest stability.

For head differences $\Delta H < 2$m no erosion was observed in the R3 series (Figure 6). Thus, the standard HET setup was changed to account for higher loads.

Table 2. HET erosion index I_e for 5 test series

Ie [-]	M1	M2	MC*	Clay
HET Irstea	3.5		2.9	
HET R1		4.0		4.1
HET R2		3.5-5.5		
HET R3		(>6.0)*		
HET R4		4.5-6.0		

*no erosion with high head diff. over long time

Table 3. HET critical shear stress τ_c for 5 test series

τ_c [N/m²]	M1	M2	MC*	Clay
HET Irstea	350		153	
HET R1		100-250		180
HET R2		103-240		
HET R3		n/a		
HET R4		370-1,500		

*marsh clay

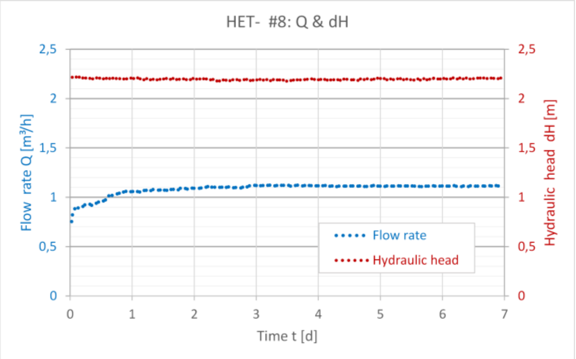

Figure 6. HET results R3 #8; 7 days of continuous high load and stagnating flow rate

4 DISCUSSION

For the DMs the evaluation of the hole erosion test is problematic. The theory to determine the characteristic curves and parameters is based on the assumption that erosion occurs rather continously (particle by particle). After an initial widening of the hole, where loose material from the hole drilling is removed, erosion should start slowly (when exceeding τ_c) and then accelerate with increasing hydraulic gradient and flow rate. However, the DMs mostly erode in larger agglomerates rather discontinously, sometimes even blocking parts of the hole before finally being washed out. It is therefore difficult to determine a reliable critical shear stress which is needed to compute the other parameters with eq. (1), (2). An example is provided in Figure 7, showing a discrete increase in hydraulic head difference resulting in very small amounts of erosion only at the beginning of the load increase and stagnating afterwards, comparable to Figure 6.

Figure 8 shows the interpretation problem where to define the linear part of the curve which is important to determine τ_c. Here, a critical shear stress of 600 N/m² is determined, a very high value compared to those presented in Wan & Fell (2004). In this particular test erosion started with a head difference of 7.56 m and a real failure (considerable hole widening) was observed for 9.48 m.

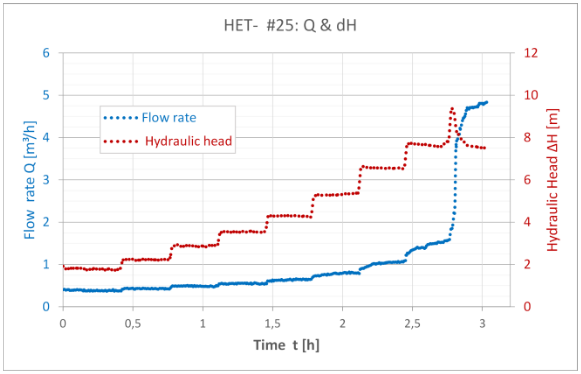

Figure 7. HET results -#25 with 9 different pressure steps, collapse at $\Delta H \approx 9$ m

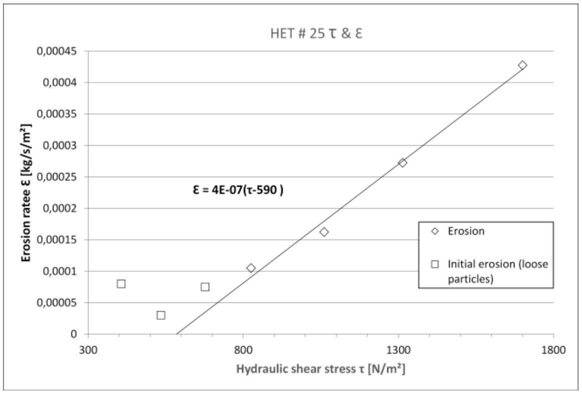

Figure 8. HET results -#25, erosion rate, initiation of erosion

Field observations on the DredgDikes research dike showed that water flow through dessication cracks and animal bore holes as well as overflow on partly destroyed vegetation cover did not result in considerable erosion, as was expected from the previous laboratory studies. Therefore, the internal erosion tests were performed to investigate the phenomenon. While well compacted M2 samples from the field site performed best in the HET even the less compacted material and remolded samples showed a good performance regarding internal piping erosion.

In Table 4 the results of the investigations are compared for the different parameters scaled to the value of marsh clay. It is obvious that the lab flume and disintegration tests show similar trends, always the marsh clay being the best performer and M2 the best DM. In the internal erosion tests the DMs usually perform at least as good as the marsh clay. This supports the experience from the field tests.

Table 4. Comparing the results, scaled to marsh clay

Test	**M1**	**M2**	**M3**	**MC***
Lab flume ε	31	9	45	1
DT Endell	2.2	1.8	2.1	1
DT Weißmann	38	15	54	1
HET I_e	1.2	1.2->2		1
HET τ_c	2.3	0.65-10		1

* marsh clay

5 CONCLUSIONS

The investigations show that the DMs under consideration possess considerable stability against piping erosion, indeed better than the current standard materials for dike covers. This is most probably due to the stable agglomerate structure of the DMs. On the other hand, the stability against surface erosion of the bare soil is rather low to medium and comparable to a standard mixed soil. Because the DMs‘ high water holding capacity and fertility they provide a very good turf. Together with a strong grass vegetation for surface erosion protection the materials possess a very high potential to be used as dike cover replacement materials.

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