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WATER BALANCE OF DIKES CONSTRUCTED WITH DREDGED MATERIAL – RESULTS FROM A LONG-TERM FIELD TEST

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Abstract. The application of processed fine-grained harbour sediments in dike constructions seems to be a solution, which protects marsh areas from sediment excavation and avoids the landfilling of these sediments. However, the long-term hydrologic behaviour and the mobilization of contaminants under in-situ conditions were unknown not only for the specific sediments dredged from the Hamburg harbour. Thus in 2004 two test fields have been constructed on a flood side of a channel closure. Whereas the reference test fields consist of 1 m clayey marsh sediments above the inner sand layer of the dike, within the second test field only 0.3 m marsh sediments are overlying 0.7 m of processed fine-grained dredged material. The construction and the additional installation of measuring devices allow the quantification of daily bottom fluxes and the course of water contents within the dike cover layers. After nine years of data collection and based on the differences in soil properties, the temporal development of the water balance of both test fields is analysed. The ongoing investigations and further modelling of water flows have to answer the fundamental question, if under the hydraulic pressure of a storm tide the difference in both cover systems is security relevant or not.

Keywords: dike cover, compaction, bulk density, leachate generation, soil ripening, storm tide

1. Introduction

Dikes are necessary earthen buildings to protect areas and goods from flooding. To perform as intended, the individual components have to meet specific demands regarding hydraulic conductivity (DWA-Arbeitsgruppe WW-7.3, 2005). For the construction of the outer layer of the dikes along the German coastline fine-grained marsh sediment is the typical substrate. However, the application of these sediments conflicts with the predominant agricultural land-use and other aims of land use planning for the marsh areas. Therefore the application of processed fine-grained harbour sediments seems to be a solution, which protects marsh areas from sediment excavation and avoids the landfilling of these sediments.

Due to the continuous decrease of the level of contamination of Hamburg harbour sediments in the last decades the Hamburg Port Authority investigates the option of substituting a part of the fine-grained layer in dike construction with processed dredged material. The processing takes place in the METHA (Mechanical Treatment of Harbour Sediments), a plant which produces a de-watered and sand-depleted fine-grain material of a high degree of homogeneity (Detzner and Knies, 2004). The desired initial low hydraulic conductivity was known for these sediments (Tresselt et al., 1998; Gröngröft et al., 2005), however, these properties may change within ongoing soil ripening (Gröngröft et al., 2002). In order to investigate the suitability of the pre-treated dredged material in dike construction under realistic conditions, Hamburg Port Authority commissioned a long term field study which commenced in 2004.

In contrast to other types of harbour sediment disposal the integration of dredged material in dike layers is combined with the ingress of oxygen and thus the potential to mobilize heavy metals. The constructed test fields thus aim at i) the monitoring of the hydraulic behaviour and ii) the analysis of contaminant leaching under in-situ conditions.

This paper focuses on the water balance of both test fields and its modification by the types of cover system.

2. Construction of test fields

In August 2004 two test fields were integrated in the flood side of a channel filling within the Hamburg harbour ("Rodewischhafen"). At the foot slope, the embankment leads into a harbour basin which is connected to the Elbe River, thus the test fields are exposed to tidal influence. A vertical section through the test field containing dredged material (test field 2) is given in Fig 3, showing the relevant elements:

- First, a sand layer was constructed to form a slope of 1:3.
- In this layer, a HDPE tray was integrated (9 * 11 m) to enable leachate collection.
- Above, three layers of processed dredged material and one layer of marsh sediments were constructed using a small sheep-foot compactor (Fig 2). In the lowest layer, the edge of the HDPE tray was integrated.
- A mixture of grass seeds was applied in October 2004 to secure a rapid greening.

In contrast, the reference test field (test field 1) was constructed without dredged material; here four layers of clayey marsh sediment were installed. From all layers disturbed and undisturbed samples were collected on the day of construction and standard soil chemical and physical analysis conducted.

The height of the basis of the test fields is +4.3 m above MSL, the top of the slope at +6.80 m MSL, the sloping is 1:3.

To collect the leachate the bottom of the tray was connected via a pipe to an HDPE collection chamber. This chamber was positioned centrally between the test fields. Within the chamber, a divider guarantees that the leachate of both test fields could be sampled separately and quantified with a water level sensor on each side. If in each half of the chamber the water level rises to about 80 cm, a switch starts an immersion pump which transports the water to a second chamber installed at the

Fig 1. Construction of the test fields in August 2004: Construction of the cover layer (marsh sediment) on layers of processed dredged material. On the left: collection chamber

Fig 2. Construction of the test fields in August 2004: Compaction of layers of marsh sediment

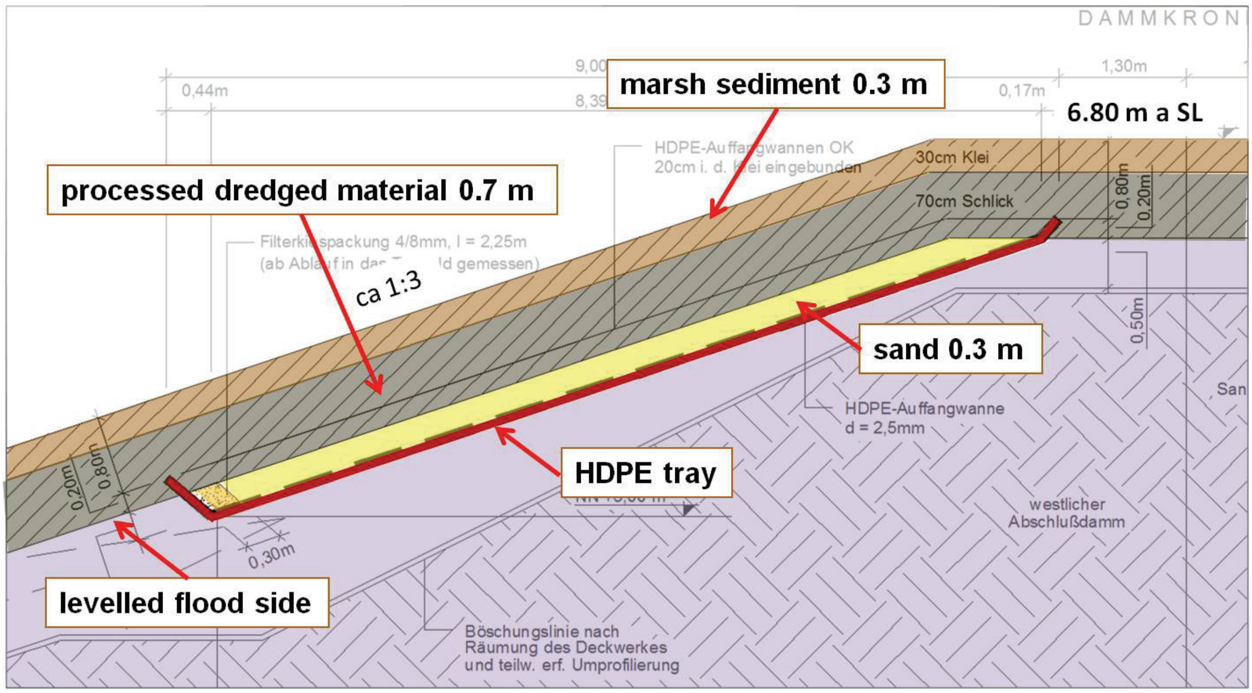

Fig 3. Vertical cut through test field 2

top of the embankment. Here, an electromagnetic flow meter measures the amount of through flowing water, afterwards the water is allowed to infiltrate in the sandy subsoil.

The measuring devices are:

- automatic water level sensors (PLog520PA-INT, Driesen+Kern, Germany), measurement interval = 15 min
- electromagnetic flow meter (promag 520, Endress+Hauser, Germany), manual readings
- climate station with air temperature, humidity and precipitation sensors (Combilog, Theodor Friedrichs, Germany), measurement interval = 1 hour

3. Data collection and processing

The test fields are controlled every 1 to 2 weeks and all data retrieved from the data loggers. Based on the water level readings (15 minute intervals), the volume of the chamber halves and the area of the test fields the leachate generation could be quantified in l m^{-2}. This amount of leachate registered by the automatic water level sensors was compared to the manual readings of the cumulative volume of leachate pumped through the electromagnetic flow meters. These data showed good agreements in normal periods.

In order to investigate the physical properties of the materials eight years after construction, the test dike was excavated in the area outside the HDPE tray (constructed in the same fashion as within the area of the tray) in April 2012. In the open pit the soil structure was examined and samples collected and analysed in the laboratory for the same properties as in the year of construction.

4. Results

4.1. Physical characteristics of the materials

In Fig 4 the result of particle size analysis is given. Two charges of marsh sediments have been used. The lower layers of test field 1 are constructed with materials of nearly 40 % clay whereas the top layer of both fields has clay proportions of about 20 %. This percentage is similar to the dredged material applied in test field 2.

In contrast to the marsh sediments, the layer constructed from processed dredged material had a significantly higher total pore volume (however predominantly in the smallest size class (< 0.2 µm, see Table 1). Also the proportion of pores > 50 µm was slightly higher than for the marsh sediments

Corresponding to the pore space distribution, the mean bulk density of the dredged material layers was 0.95 g cm^{-3} compared to 1.41 g cm^{-3} for the layers constructed from fine-grained marsh sediments. An additional difference was found in the amount of organic carbon, which ranged from 3.3 – 6.0 % for the dredged material and 2.0 – 2.1 % for the marsh sediments at the time of construction.

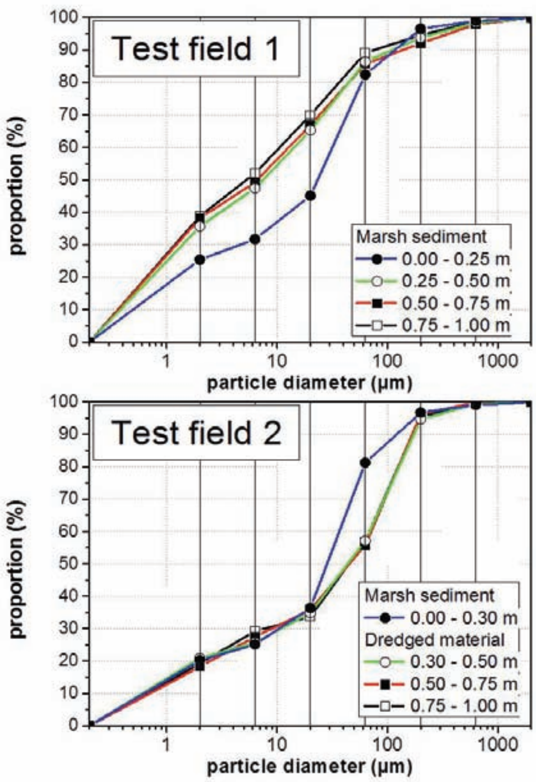

Fig 4. Results of texture analysis

Table 1. Results of pore space analysis (construction state)

	Layer	Substrate	Total pore volume (%)	Pores < 0.2 µm (%)	Pores 0.2 – 10 µm (%)	Pores 10 – 50 µm (%)	Pores > 50 µm (%)
TF 1	1	MS	48.9	33.1	11.5	1.1	3.1
	2	MS	53.2	38.9	11.6	1.4	1.3
	3	MS	56.1	36.1	15.9	1.1	3.0
	4	MS	54.1	42.3	7.3	0.8	3.8
TF 2	1	MS	48.0	28.9	22.1	2.6	3.7
	2	DM	64.0	34.0	26.7	3.3	4.6
	3	DM	63.8	28.4	26.8	3.5	5.3
	4	DM	62.5	28.4	2.5	2.2	5.1

TF = test field; MS = marsh sediment; DM = dredged material

4.2. Course of annual leachate collection

Fig 6 gives the daily bottom flux as quantified from the water level readings in the collection chamber for the eighth year after construction as well as the course of precipitation. From the start of this period (October) to the beginning of December no leachate was collected from either test field in spite of the fact that the amount of precipitation summed up to 260 mm. The start of leachate collection in December was 11 days earlier in test field 1 than in test field 2. In this phase (until 28th of January) the difference in collected leachate volume was 17 l m^{-2}, indicating that the soil cover in test field 2 was able to retain more water before bottom flux started. Later in the winter season, the leachate generation reacts to precipitation inputs with delayed outflow, however nearly synchronously in both test fields.

Fig 5 shows the cumulated seepage of both test fields from the construction in 2004 to the recent date (end December 2013), i.e. for nine years. The course of leachate generation of both test fields can be separated into three phases. The first phase started with the construction and ended two years later (end of 2006). This phase was characterized by zero (test field 1) or very low (test field 2) bottom flux. In the second phase (end of 2006 to summer 2008) the seepage increased strongly for test field 2 (total seepage 710 mm in 2 years). The seepage rate of test field 1 also increased but then remained rather constant the following years. The third phase was characterized by dynamic seepage as shown in Fig 6. Bottom fluxes typically occurred in the late winter and in spring months whereas in summer and autumn the fluxes disappeared totally or nearly totally.

4.3 Water balances

In Table 2 the components of the annual water balances of both test fields are given for nine years of investigation. Precipitation as the dominant input varied between 590 and 900 l m^{-2}, the climatic water balance, calculated from precipitation minus potential evapotranspiration ranged from – 43 to +375 l m^{-2}. Also given is the number of storm tides which exceeded the bottom level of the test fields (4.3 m above MSL).

The first phase of test field operation, as indicated above, was characterized by a negative climatic water balance. Here, especially the period from April to September 2005 (-174 l m^{-2}) and from May to July 2006 (- 280 l m^{-2}) has to be mentioned. Also the hydrological year 2008/09 had a negative water balance.

The annual bottom flux of the test fields varied strongly, depending predominantly on the climatic water balance. For test field 1, the linear correlation between both parameter resulted in R^2 = 0.377, for test field 2 in R^2 = 0.147, respectively.

Additionally to inputs from precipitation, water can in filtrate into the flood side of the dike during storm tides. Although in the past technical problems led to insufficient data retrieval during some storm tides, quantification was successful on the storm tide at 31st of January 2013. For this storm tide, the maximum Elbe water level was 0.43 m above the bottom of the test fields and the lower parts of both fields were flooded for 140 minutes.

Table 2. Components of annual water balance (Oct – Sept);

Year	P	CWB	BF TF1	BF TF2	THW
	l m^{-2}	l m^{-2}	l m^{-2}	l m^{-2}	
2004/05	728.8	-13.2	0.0	10.7	2
2005/06	724.7	-43.3	12.3	30.4	0
2006/07	895.5	227.0	100.7	330.9	2
2007/08	834.6	193.2	103.3	378.1	1
2008/09	587.7	-31.3	75.4	54.0	0
2009/10	889.4	375.2	163.7	176.0	
2010/11	676.4	142.7	170.1	246.6	
2011/12	735.9	260.1	167.0	252.4	
2012/13	773.4	290.5	148.7	171.7	1

P=precipitation; CWB = climatic water balance; BF = Bottom flux; TF = test field; THW= no of storm tides exceeding bottom level of test fields)

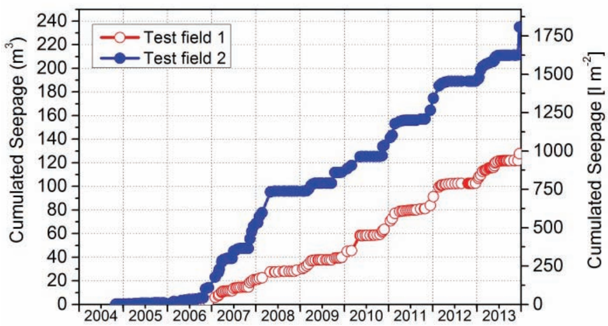

Fig 5. Cumulative seepage of both test fields

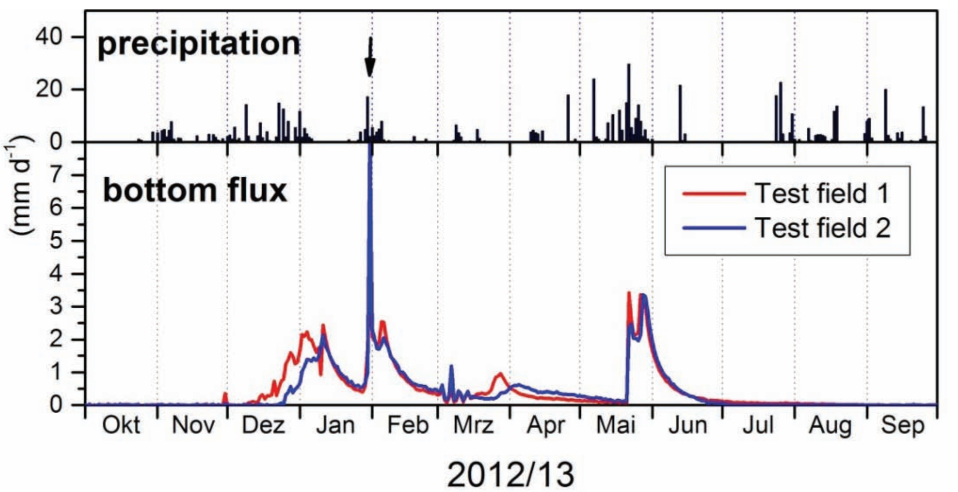

Fig 6. Leachate generation in the year 2012/13 (arrow marks input by storm tide)

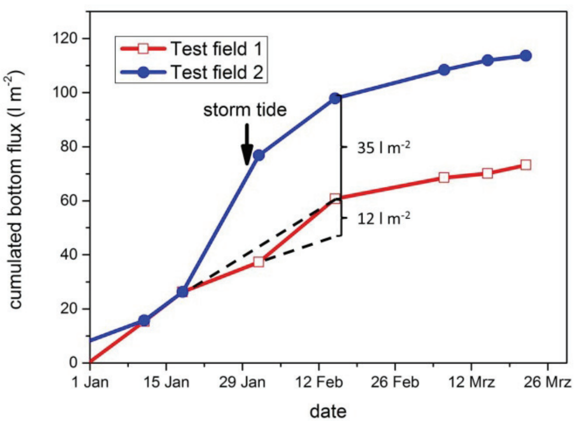

Fig 7. Bottom flux of both test fields at storm tide 31.1.2013 (arrow)

Fig 7 shows the course of bottom fluxes for both test fields. The difference between extrapolated flux without storm tide and measured flux summed up to 12 l m^{-2} for test field 1 and 35 l m^{-2} for test field 2, both values calculated for the area of the whole test field.

5. Discussion

The in-situ measurements of the seepage rate of flood side covers of dikes is a technique to study the hydraulic behaviour of dikes under conditions of hydraulic normality as well as under hydraulic pressure. To the author's knowledge, the current study applies this technique for the first time. It helps to investigate the effect of different factors controlling or influencing the hydraulic behaviour, which cannot be studied under laboratory conditions sufficiently. Here, especially the interactions between the soil materials, vegetation and soil organisms and their direct or indirect influences on water fluxes through the soil have to be mentioned. The measured flow rates are an indicator for the soil structuring processes and the development of the vegetation along the flood side of the studied test dike.

The low leachate collection values during the first two years after construction are likely to be explained by the following factors:

Both cover materials had very low initial hydraulic conductivities due to the compacting construction practice ($<2.8*10^{-9}$ m s^{-1}). For the dredged material, these conductivities were in the range as found for the construction of mineral liners of landfills (Tresselt, 2000), the conductivities of the marsh sediments were even lower. Although in the first winter there was a climatic surplus of 160 l m^{-2}, no bottom flux could be collected due to this low hydraulic conductivity and surface runoff must have occurred. Initially, both types of materials have reached nearly water saturated conditions due to the compaction process. The low bottom fluxes of the test field 2 in the first phase could be explained by a consolidation of the material combined with a loss of pore water. Initially, the seepage exhibited anaerobic conditions indicated by high concentrations of ammonium (Gebert et al. 2010). Most likely the first phase could have had lasted longer, if the first both vegetation periods had not been that dry. In these periods, by expanding their roots the growing grass vegetation was able to take up large amounts of stored water from the cover layers. From the pore space analysis it was found, that the available amount was about twice as high in the test field constructed with dredged material (about 300 l m^{-2} in 1 m depth) than in test field 1 constructed with pure marsh sediments. However, the de-watering of both materials resulted in shrinkage, which was easily visible from the soil surface.

For the dredged material, the structural development can be described as soil ripening, a process which is common in cases of diking of marine sediments for land reclamation (e.g. Vermeulen et al., 2005; Pons and Zonneveld, 1965). Irreversible shrinkage leads the development of permanent vertical cracks, which have been found in dimensions of 1-2 cm thickness by soil investigations in 2012. The ongoing soil analyses (see Oing et al., 2014) will concentrate on the change in soil physical properties by this material.

In contrast, for the marsh sediment processes of soil ripening have been finished for long. The shrink-swell-behaviour is reversible and thus cracks formed in the summery dry seasons typically close with wetting during autumn and winter.

The differences in annual seepage through the cover layers of both test fields can be explained by two effects: The higher water storage capacity of the test field build with dredged material results in a longer phase of water uptake at the beginning of the winter season. If the water content is equilibrated, then the higher hydraulic conductivity of this cover leads to less surface runoff and thus to larger amounts of seepage. However, the differences between both cover systems are reduced by the top 30 cm layer, which is the same in both test fields.

The fundamental question, whether the difference in seepage of both cover systems under conditions of hydraulic stress (here storm tides) is of relevance has not been solved yet. The absolute amount of seepage in the storm tide of January 2013 seems to be acceptable, however for robust conclusions further studies on the water flows under high river water conditions have to be conducted. Here, also simulation runs for different types of dike constructions are necessary.

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