Comparison of two Methods to Evaluate the Data from Seepage Tests at the German DredgDikes Research Dike

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Abstract. The project DredgDikes was initiated by the University of Rostock and the Technical University of Gdansk to investigate the usability of dredged materials in dike construction. In the German subprojects ripened fine-grained organic dredged materials are used as dike cover materials. In May 2012 the German research dike was built in Rostock-Markgrafenheide to perform full-scale experiments. The test dike has been constructed as a three polder system and consists of eight different sections with different slope inclinations, materials, and geosynthetic solutions. During the construction work and after completion of the research dike, different sensors such as tensiometers, moisture sensors, tipping counters and standpipes have been installed to detect the seepage line in case of hydraulic loading. One year after completion of the test dike, eight seepage experiments have been performed from May to August 2013. Each of the three polders was filled repeatedly and moisture, soil water tension and water level data have been recorded.

To evaluate differences between the materials and cross-sections the collected data was rated in a matrix to gain first qualitative results. This qualitative comparison shows that the cross-sections with geosynthetic in-plane reinforcement allows less seepage water to enter the dike core compared to the cross-sections without reinforcement. A statistic method, PBIAS, was used to detect differences and correlations between the used materials and geosynthetic solutions. It was discovered that there are negligible small differences between the two used materials if the thickness of the cover layer is 1.0 m. A thicker cover tends to be less susceptible against impacts like mouse holes and cracks. In the near future the results will be compared to a numerical model data. The solution with an erosion product tends to be less permeable than the other solutions.

Keywords: dredged materials, dike, seepage line, moisture sensors

1. Introduction

Floods and storm surges have become more frequent during the past few decades, with increasing peaks and longer duration of flood events. Consequently damaged dikes need reconstruction and many existing protection structures need increased crest levels to provide better protection of the hinterland. On dikes at the Baltic coast of Mecklenburg-West Pomerania usually marl has been used as dike cover material which is a natural resource often mined in environmentally sensitive areas. Therefore, alternative dike construction materials are gaining importance, regarding both the protection of marl as a natural resource and of the environment.

For the navigability of waterways and harbour facilities, dredging works are necessary. The sediments are mostly relocated or taken out of the water. The dredged materials vary in mineralogical and chemical composition and characteristics along the coast. A great percentage of these materials are not contaminated, hence the sediments could be used to replace other construction materials. Dredged materials have already been used as recultivation layers for landfills, in agriculture, backfilling of new land in harbours, and some attempts in dike constructions have been made (HTG 2006). Still, the application of fine-grained and organic dredged materials in dike construction is a rather new idea. During the past years research activities were started at the University of Hamburg (Gröngröft et al. 2005), the TU HH-Harburg (Beyer et al. 2012), the Hamburg Port Authority, the Federal Waterways Engineering and Research Institute BAW and also through Dike associations and Bremenports (Bremischer Deichverband, 2013). The project DredgDikes was initiated by the Chair of Geotechnics and Coastal Engineering at the University of Rostock and the Technical University of Gdansk to investigate the usability of dredged materials in dike construction. In the German subproject the use of dewatered fine-grained organic dredged materials is investigated as a replacement for standard dike cover material. In May 2012, the German research dike was built near Rostock to perform full-scale experiments.

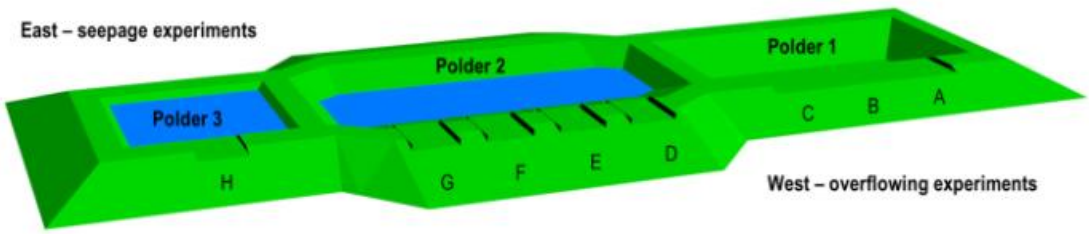

Fig. 1: 3D view of the research dike in Rostock.

2. German Research Dike

The German DredgDikes research dike is a three-polder system (Fig. 2) and consists of ten different cross-sections. Each section is 8 meters width. Vertical mineral sealing elements were placed in the sand core to separate the sections against each other and to prevent water exchange between the sections. This paper focuses on polder 1 and polder 2 which consist of a 2 m high sand core and a cohesive cover made of either material M1 (A, F, G) or M2 (B, C, D, E). The layer thickness of the outer slope of the sections A to C is 1.5 m. The inner slopes of these three sections have a thickness of 1 m. In Polder 2 the cover layer is consistently 1 m thick. Polder 3 is a homogenous solution and constructed with material M3 (H). The dike is in general 3.3 m high, with a slope inclination of 3:1 on both sides in polder 2, and 2:1 in the other two polders. The polder system is divided in the western side, which is mainly used for the overtopping experiments (Olschewski et al), and in the eastern side to detect the seepage line. Two different erosion control grids were used in the research dike. A geosynthetic reinforcement product was installed in plane of the cover layer in the eastern sections of E and F to reduce shrinkage cracking. The high clay content together with the organics and high initial water content leads to considerable cracking. If deep cracks reach the sand core the system is particularly critical. With the reinforcement installed, an increased number of smaller cracks was expected and thus less seepage. The three-dimensional geosynthetic erosion control grid (Huesker Fortrac 3D) was installed, because a good frictional behaviour was considered to be more important than high tensile strength. Moreover, the resistance between soil and reinforcement grid needs to be high, even for very small displacements (Cantré, Saathoff 2014). The product was installed at the outer slope in 0.3 m and 0.5 m depth and at the inner slope in 0.3 m depth of the cover layer during the construction (Fig. 1). The second erosion product covers sections C and the western parts of section E and F (Enkamat). Underneath the whole research dike a geosynthetic clay liner (GCL) was installed to shield the testing area against the underground. This construction ensures that the water will not infiltrate into the building ground during filling tests and give a closed system for the analysis. Hence the water will only flow through the single sections. The bottom sealing does not correspond to natural conditions; however, it is necessary for the full-scale experiments.

2.1 Used Dredged Materials

The dredged materials which were built in as cover layers in this project are defined as materials M1, M2 and M3. The materials were dredged from the Warnow river delta to ensure the navigability of coastal waterways and harbour facilities in Rostock. The dredged materials with high organic and lime contents were dried and processed on the containment facilities of the Hanseatic city of Rostock. The geotechnical characterization was performed according to German DIN-standards at the Uni-versity of Rostock. The fine-grained dredged materials M1 and M2 are mainly characterized by high water, organic, and lime content, which has considerable influence on other geotechnical para-meters (Saathoff et. al. 2014). The permeability for material M1 was determined with 4-6E-08 m/s. While the permeability of material M2 is nearly two decimal powers less than material M1, with kf=7-9E-10 m/s (Große & Saathoff 2014).

2.2 Measurement set up

To find a reasonable measurement set up the first results of the laboratory tests were used to simulate seepage through the constructed dike sections. Mainly the permeability was decisive for this procedure. It is known that the permeability in the full-scale construction is two decimal powers higher than the determined values in the laboratory. After the simulation of a cross section with the higher permeability values the placement of the sensors was planned.

The measurement setup was mainly installed at the eastern side of the polder system during the construction work in summer 2012 and after the finalisation of the research dike. The instrumentation was installed in the centre of each section. The set-up of the measurement devices is almost similar in each section, with two standpipes on the crest, a tip counter at the toe of the inner slope (only B to G), generally three moisture sensors type EC5 (only in D there are five), one Theta Probe moisture sensor at the toe of the outer

slope, and five tensiometers at the outer slope (Fig. 2).
Standpipes were set up on the crest of the dike, one to the outer slope and one to the inner slope. On the eastern side the water level inside the standpipe near to outer slope (EE) was detect through a pressure sensor at the bottom of the pipe. The water level in the other pipes (EW, WW, WE) was measured by an electric contact gauge. These simple set up ensures the comparison between the eastern side and the western side.
Two different kinds of sensors based on frequency domain refletometry (FDR) are used to measure the moisture of the sand core and the cover layer. Both sensors recording mV signals and were calibrated in the laboratory to be able to compute the volumetric water content from the mV signals. The EH20-EC5 (EC5) sensors are comparably small and low-cost and were installed during the construction works of the research dike inside the sand core. After a layer of 0.5 m thickness was built up, a 0.4 m deep hole was dug in the compacted sand by hand. The EC5 sensor was installed at the bottom of the hole and the cavity was closed afterwards, using the excavated sand, and compacted by hand. Afterwards, the construction machinery was able to move on the sand core without causing any damages to the sensors. The Theta Probes are the second FDR sensors, which were used. They were installed after completion of the construction in the toe of the outer slope of the cover layer (Fig. 2).
To collect and record the volume of the seepage water at each toe of the outer slopes of sections B-G (east) a tipping counter was installed respectively after completion of the research dike. During the construction work, strips of geosynthetic drainage composite with a width of 1 m were installed at the toe of each of the six sand cores to the land side. They were connected to drainage pipes, leading the seepage water out of the construction into the tipping counters.
Tensiometers (UGT TENSIO 152) are installed for long-term monitoring of the dike cover materials. The sensors were used to measure the excess water pressure to -30 kPa and the suction pressure of the soil up to 100 kPa. In every section tensiometers are installed vertically to the slope in a depth of 0.4 m (three sensors) and in the depth of 0.2 m (two sensors, Fig. 2). The tensiometers are referred to according to their position in the dike slope (B=bottom, M=middle, T=top, C=crest). The number in the nomenclature gives information about the installation depth of the tensiometers in the cover layer (02= 0.2 m depth, 04=0.4 m depth, 10=1.0m depth). To work with a closed system for the analysis, the geosynthetic clay liner is defined as the reference plane. All sensors were surveyed with a tacheometer to define the relative level above this plane. Each polder is equipped with a data logger were all sensors are connected and which can be accessed by a network computer. During the filling experiments, the logging time of

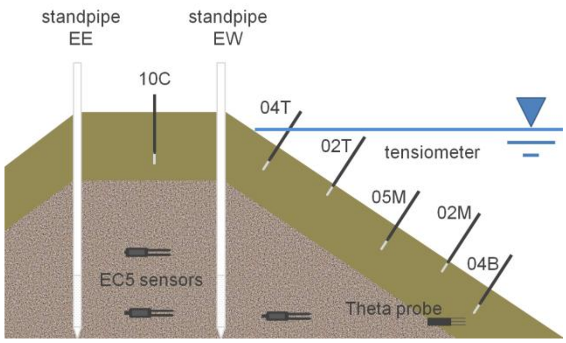

Fig. 2: Schematic view of a cross section.

all sensors was set to one minute to record the minimum, maximum, and average value every 15 minutes.
Together with the meteorological station which was placed close to the research dike, soil hydrological evaluations can be performed.

3. Analysis of the measured data

Only the filling tests of polder 1 and polder 2 were evaluated in this paper.

3.1 Filling tests

In polder 2, three filling experiments were performed. The filling of the polder during overflowing experiments was defined as the fourth test (Fig. 3). In polder 2, only the first two experiments were performed as filling tests. The other two filling test, filling 3 and filling 4 (Fig. 4) were performed during the overflowing experiments (Olschewski et al. 2014). The general process for the experiments was to fill a polder in approx. one to three days. Afterwards, the water level was kept on the same level (+/- 0.1 m) for seven days. The polder was emptied in a few hours. The first filling experiments were realised using a pump with a maximum surcharge of 70 m³/h. Because of different positions of the pumps on the research site and the resulting differences in hydraulic resistance, the time to fill the polder varied. For the overflowing tests, two huge pumps with a maximum surcharge of 350 m³/h each were used. This allowed filling the polder within three hours. Therefore the hydrographs in Błąd! Nie można odnaleźć źródła odwołania. and Fig. 4 do not show the same slope.

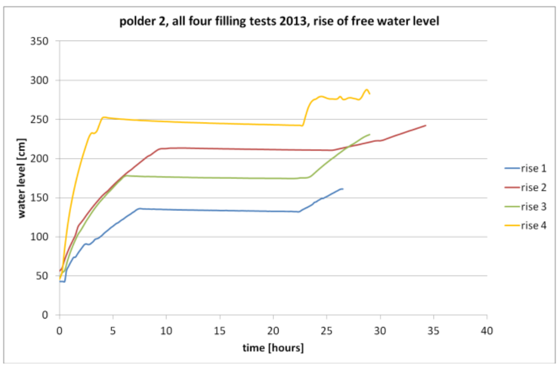

Fig. 3: Polder 2 - all filling tests 2013 - rise of free water level.

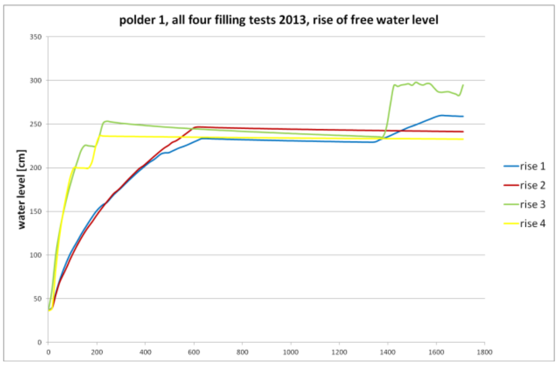

Fig. 4: Polder 1 - all filling tests 2013 - rise of free water level.

3.2 Evaluation method - matrix rating

The first evaluation step was to interpret the graphs of each sensor to find differences between the measured data of the different cross sections. For this step diagrams were used like Fig. 5 to rate each section. For the graphs which showed the lowest permeability the value 1 is chosen and -1 stands for the fastest moisture penetration derived from direct comparison of the data graphs. The graphs placed between the highest and lowest rate are equally rated 0. The rating process will be described using Fig. 5 as an example: The solid light blue curve shows that the sand core in section G fills fastest and the seepage line increases highest inside the dike core. In case of a dike construction, this case clearly needs the lowest rating. Therefore, the matrix value of the sensor standpipe EW for filling test 2 in section G is -1. The dashed light green graph is the measurement from section E. It shows that the seepage line does not rise as high as in the other three sections. This case is the best among the four other curves and thus rated 1. In the matrix (Fig. 6) each sensor of each section (D to G) and filling test (F1 to F4) is rated. Both curves that lie between the other two are equally rated 0. The evaluation was done based on the height of the curves, the rising time (fastest, slowest), and the gradient of the curves (steepest and flattest).

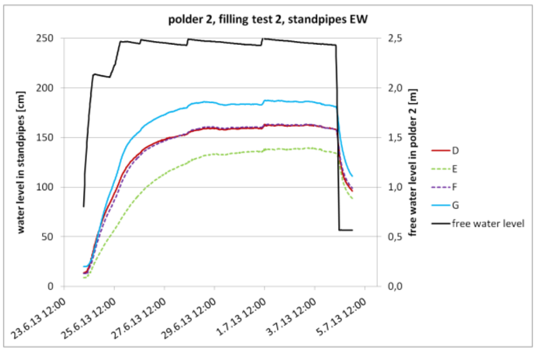

Fig. 5: Polder 2 - filling test 2 - standpipes EW.

During the first analysis of the whole test series, all sensors were treated equally. In Fig. 6, the red box stands for value -1, the green box represents value 1, and yellow represents the middle curves.
This method is used for the evaluation of all four filling tests in polder 2 and for the first three experiments in polder 1.

3.3 Evaluation method - PBIAS method

The matrix method provided qualitative information to compare the different cross sections. To evaluate the measured data and detect differences and accordance's between the different sections a good method was needed to obtain quantitative results.
In general different approaches are known to evaluate the results of simulated data (Moriasi 2007, Kumar et. al. 2012). "The slope and y-intercept of the best-fit regression line can indicate how well simulated data match measured data" (Moriasi 2007, p. 887). The approach of the coefficient of determination (R^2) is commonly used as well. The value describes the degree of colinearity between simulated and measured data (Moriasi 2007). The percent bias (PBIAS) is a tool to calculate the deviation of computer generated data (sim) of the actually measured values (obs) (Moriasi 2007). A value of 0.0 describes perfect agreement between measured and simulated data.

		TEN 04B	Theta Probe	TEN 02M	EC5	TEN 02T	TEN 04M	TEN 05T	Standpipe EW	Standpipe EE	Tipping counter
D	F1	0	0	-1	0	1	-1	-1	0	0	0
	F2	-1	-1	-1	-1	0	-1	-1	0	0	0
	F3	-1	0	-1	0	0	-1	-1	0	0	-1
	F4	0	-1	-1	-1	0	-1	-1	0	#NV	#NV
E	F1	-1	0	0	0	0	0	0	1	1	1
	F2	1	1	0	1	-1	-1	-1	1	1	1
	F3	-1	-1	-1	0	-1	-1	0	1	1	1
	F4	-1	0	-1	1	-1	-1	0	1	#NV	#NV
F	F1	1	1	1	1	0	1	1	0	0	1
	F2	1	0	1	0	1	1	1	0	0	0
	F3	1	1	1	1	1	1	1	0	0	0
	F4	1	0	1	0	1	1	1	0	#NV	#NV
G	F1	#NV	-1	0	-1	-1	0	0	-1	-1	-1
	F2	#NV	0	-1	0	0	0	0	-1	-1	-1
	F3	#NV	0	-1	-1	0	0	0	-1	-1	-1
	F4	#NV	0	-1	0	0	0	0	-1	#NV	#NV

Fig. 6: Matrix rating of polder 2.

If the model is underestimated the PBIAS indicates positive values. Negative PBIAS values show model overestimation. PBIAS values can be calculated with the aid of equation 1.

$$PBIAS = \frac{\sum_{i=1}^{n}(Y_i^{obs} - Y_i^{sim}) * 100}{\sum_{i=1}^{n}(Y_i^{obs})} \quad (1)$$

In this paper the method of PBIAS was not used to compare between simulated and observed data but to compare the measured data of different cross-sections. Positive PBIAS values indicate that the first mentioned section tend to be more permeable than the second section which it is compared with. On the other hand, a negative value shows that the first mentioned section is less permeable than the second one.
To begin with the two materials (M1 and M2) were compared by using equation 2.

$$PBIAS = \frac{\sum_{i=1}^{n}(Y_i^{M2} - Y_i^{M1}) * 100}{\sum_{i=1}^{n}(Y_i^{M2})} \quad (2)$$

Fig. 7 shows the result of the calculation. The data gained from the water level inside the standpipes was used for this PBIAS evaluation. Material M2 (D, E, B) was compared with material M1 (G, F, A) from both polder 2 (DG; EF) and polder 1 (BA). During the first filling test a deviation of about -20% occurred between the two materials in the first two examples (DG: without geogrid and EF: with geogrid). This deviation decreases in general with further filling tests.
In the third example the cross section B consists of material M2 and is compared with section A (material M1). In this case a huge difference between these cross sections of nearly -100% can be observed. The deviation decreases significantly with further filling tests as well. To detect differences between the sections with and without a geosynthetic solution equation 3 was used. In this case sections with the same material but with different construction solutions were compared.

$$PBIAS = \frac{\sum_{i=1}^{n}(Y_i^{without} - Y_i^{with}) * 100}{\sum_{i=1}^{n}(Y_i^{without})} \quad (3)$$

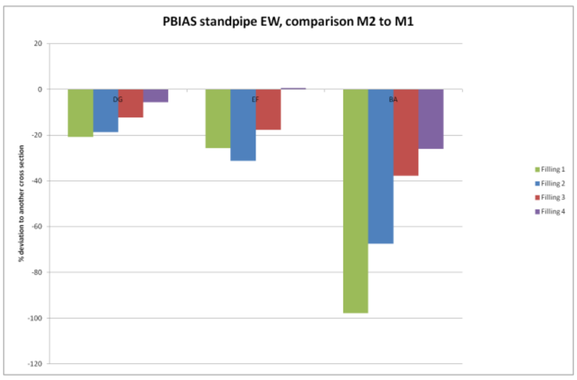

Fig. 7: PBIAS - standpipe EW - comparison M2 to M1.

Fig. 8 shows the comparison by means of the PBIAS method of the same material in different cross sections. It compares cross sections with a geosynthetic solution (E; F; C) with cross sections without a geogrid or erosion product (D; G; B). A geogrid is installed in section E and F and an erosion product in section C. The sections D/E and B/C contain material M1 and the sections G/F were constructed with material M2. The thickness of the cover layer is 1m in polder 2 (DE; GF) and 1,5m in polder1 (BC). No significant deviation of the cross sections with a geogrid can be observed compared with the cross sections without such a solution (DE and GF). Less than 20% deviations is observed which decreases with further filling test. A much more significant deviation can be observed in polder 1 were an erosion product was used (C) and the cover layer is 0,5m thicker. But with further filling no trend can be observed in polder 1. The deviation varies from 15% to 400%.
The measured data of the tensiometers were compared with the help of the PBIAS equation as well. Fig. 9 shows an example for the comparison of the sections D and E. The first three bars represent the results from the standpipes. The PBIAS deviation based on the standpipe values is around +20% for all three filling tests. The next five bar charts (three bars each) show the results of the PBIAS calculation based on the tensiometer values. It can be seen that there is no uniform trend for each tensionmeter for different filling experiments. In addition no trend for the PBIAS deviation for the five different tensiometers in the same filling test

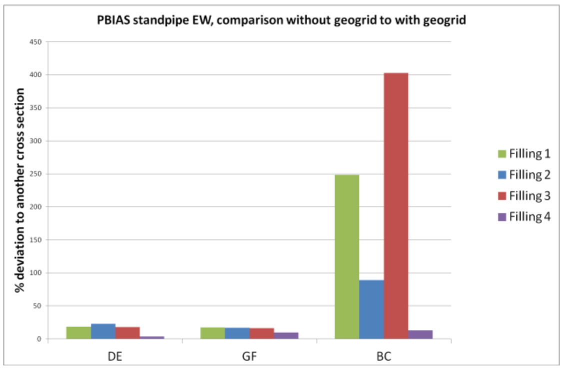

Fig. 8: PBIAS - standpipe EW - comparison without/with geosynthetic solution.

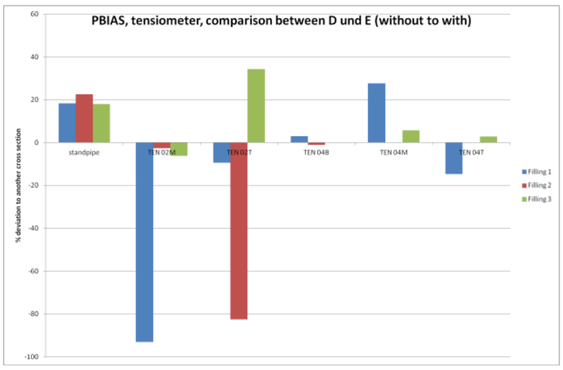

Fig. 9: PBIAS - tensiometers - comparison between D and E (without/with geosynthetic solution)

can be observed. The values are more or less scattered. Therefore no further tensiometer values were used for the evaluation by means of the PBIAS.
The evaluation with the aid of the average tendency between the comparative sections (PBIAS) for the EC5 sensors, the tipping counters and the theta probes will be finished in June 2014.

4. Discussion of the measured data

After the first qualitative evaluation of the measured data a quantitative method was searched for further evaluation.

4.1 Results - matrix

At first each polder was evaluated individually with the aid of the matrix rating. To find differences and correlations polder 1 and 2 were rated in one matrix afterwards. To evaluate the data by means of the matrix for polder 1 and polder 2, only the sensors at the same points of the sections were used. The tensionmeters TEN 04B, M, T and TEN 02M are installed at the same place in all seven sections. The data of the EC5 B1 moisture probe, the theta probe sensor and one standpipe (EW) were used for this evaluation as well.
For each cross section the matrix values were summed up.

In Table 1 material M1 and material M2 are compared of different cross sections in the full scale experiment. Both materials show both positive and negative values. In contrast to the laboratory characterisation where significant differences between the materials were obtained, neither material M1 nor material M2 shows a significant trend. In

Table 2 sections with different con-struction solutions are compared. All sections with a geogrid reinforcement or a erosion product are referred as a section with geogrid (C, E, F). The other four sections (A, B, D, G) were constructed without such a solution. It is obvious that positive values are obtained in all cross sections with a geogrid in the cover layer or with an erosion product on the slopes.

Table 1: Matrix results from polder1 and polder2. Comparison of M1 and M2.

Material 1 M1			
A	F	G	
-5	8	-7	
Material 2 M2			
B	C	D	E
-8	7	-9	7

Table 2: Matrix results from polder1 and polder2. Comparison with/without geosynthetic solutions.

With geogrid			
C	E	F	
4	4	8	
Without geogrid			
A	B	D	G
-2	-8	-9	-4

The matrix sums for the other four sections are all negative. Table 2 indicates that the sections with a geosynthetic solution tend to perform better as dike construction solution as sections without such products.

4.2 Results - PBIAS

The percent bias (PBIAS) is a tool to calculate the deviation of computer generated data of the actually measured values (Moriasi 2007).
The PBIAS evaluation of material M1 and M2 shows that the permeability of material M2 is less than the permeability of material M1. It is obvious that for all three examples the permeability of material M2 is less than the permeability of material M1, no matter if a geogrid was used or not. The largest deviation can be observed in the solution with a thicker cover layer in polder 1 (BA – 1,5m compared to 1m in the other 2 examples).
This leads to the assumption that differences between the materials are much more significant if the thickness of the cover layer is larger. Impacts on the material like cracks, mouse wholes and macro pores seem to have a larger influence on the first layer of the dike cover. In deeper layers the permeability is not influenced as much by such impacts. The result that material M2 has a lower permeability than material M1 can be confirmed by the laboratory values as well.
Further on the PBIAS method was used to compare the same material in different cross sections. It compares cross sections with a geosynthetic so-lution (E; F; C) with sections without a geogrid or erosion product (D; G; B). No significant deviation of the cross sections with a geogrid can be observed compared with the cross sections without such a solution (DE and GF). A much more significant deviation can be observed in polder 1 were an erosion product was used and the cover layer is 0.5m thicker. But with further filling no trend can be observed in polder 1. The deviation varies from 15% to 400%.
There is no reason found for this deviation yet. The reason could be the different thickness of the cover layer as well. It is also possible that better results can be obtained in cross sections with erosion products in general. Further investigation is needed.

In summary material M2 is 20% less permeable than material M1. This is a rather marginal difference in geotechnical field testing. It can be assumed that this difference is mainly caused by inhomogeneousity and not by a difference of the two materials. The difference between the sections with a geogrid solution inside the cover layer is also small and therefore negligible. Only the cross section with the erosion product shows a significant deviation.

The results of the evaluation with the aid of the PBIAS method shows the same tendency as the matrix method had delivered, but in general the deviation between materials and construction solutions is not significant. Just the cross section with the erosion product shows a remarkable difference.

4.3 Results - instrumentation set up

The permeability was measured to be higher than assumed for the first modelling based on the laboratory values. The tensiometers data showed deviations between the tests and regarding other data recorded in the tests which may be lead back to aggregation processes, cracks and mouse holes in the upper 0.4 m of the cover layer where the tensiometers were installed. Hence, the tensiometer installation in the first half meter gave no represent-able results. Therefor a new measurement set up was planned and implemented in spring 2014 (Fig. 10). First of all the tensiometers were installed deeper inside of the cover layer. No one line measurement set up is used any more. The tension-meters D, 05 and PF are installed double in the same height with a distance of about 0.1m to each other. With this measurement set up a confirmation of the tensiometer values should be possible. The EC5 moisture sensors detect the seepage line. After technical defects of some sensors, there are less sensors on the same position in each section to compare the different cross sections. The free logger slots are used for more tensiometers now. As the GCL sealed the testing area against the underground, the dike toe of the outer slope dried very slowly. In the previous measurement set up the Theta Probe was installed 0.1m over the GCL. Because of the same water contend in the dike toe the Theta Probe showed more or less the same values all the time.

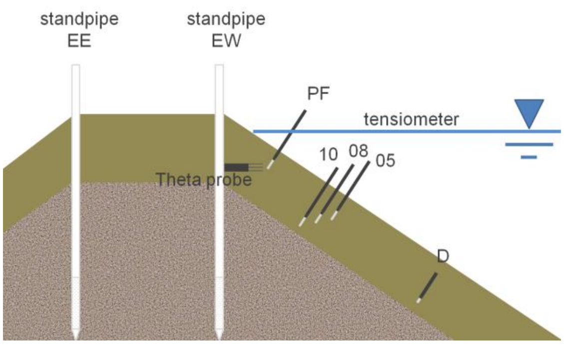

Fig. 10: New measurement set up.

Therefore the moisture sensor is now installed in the upper third of the outer slope.

5. Conclusion

The initial analysis of the data collected in four seepage tests at the Rostock DredgDikes research dike shows that some data are more reliable than others and that the performance of the different cross-sections can be rated based on the data derived and compared with a statistic method. Here, seven of eight tested cross-sections are presented.

1. There are only small differences between the chosen materials M1 and M2. The variety between the two materials is not as high as determined in the laboratory tests. Material M2 tend to be less permeable.
2. The cross-sections with a geosynthetic reinforcement product generally perform better regarding to the seepage flow (lower permeability) than those without reinforcement.
3. A layer thickness of 1.5 m tend to be better than a thickness of 1.0 m. The top level of the cover is influenced by different impacts and the cover becomes more permeable.
4. The section covered with the erosion product tend to be the best solution. This section showed the lowest permeability.

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