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GEOTECHNICAL INVESTIGATIONS ON DIKE MATERIALS AS A BASIS FOR A HOLISTIC NUMERICAL MODEL

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Abstract. At the present, dikes are designed on the basis of long time experience, specific physical models and analytical approaches. The specific exclusive aspects governing the dike resistance (e.g. crack development, influence of the grass revetment on the erosion resistance, erosion of the dike material) are examined independently in present research projects. In this paper, first examinations on glacial till dike coverings are presented. To analyse the influence of soil formation processes on the dike persistency undisturbed soil samples were taken at dikes of different ages. Field and laboratory experiments were carried out. Prior to sampling, water was infiltrated into the dike cover to simulate the exposure of the dike to high water levels. Due to the infiltration the water content of the dike cover is changed and so the indicated strength by stress-strain curves for different water contents can be determined by triaxial shear tests. The results are used as input parameters for a holistic numerical model using the Software FLAC3D in which different dike cover layers (e.g. glacial till and dredged material) with the specific stress-strain relation can be defined. Here, the dike resistance of those dike covers will be estimated for storm surge and wave attack. Using a numerical model, failure mechanisms can develop freely and the superposition of various factors can be examined. A coupled mechanical-hydraulic model of a dike cross-section is used, so that specific dike-characteristics (dike material, soil structure, etc.) under the influence of hydraulic events (storm surge, wave attack) can be analysed within the simulations. With this approach, dike damage and potential risk areas can be determined by a parameter variation and coastal protection measures can be evaluated. Besides field and laboratory experiments on existing dikes, investigations at experimental dikes are planned for the future. Here, dredged materials from German federal water ways will be used for the dike cover as an alternative to the common construction materials.

Keywords: Baltic Sea, glacial till, sea dikes, infiltration tests, soil-mechanical parameters, numerical modelling

1. Introduction

At German coasts and estuaries, dikes are usually constructed with a sand core covered by a cohesive material such as clayey marsh soil at the North Sea or glacial till at the Baltic Sea. The main purpose of the dike cover is to protect the core from erosion and to reduce water infiltration into the dike core. Judicial and ecological issues often occur with the exploitation of clayey marsh soil and glacial till. Additionally, the scarcity of clayey marsh soil and glacial till are to be expected so that the use of dredged materials, gained out of the maintenance of the German waterways, seems to be an alternative for the construction of the dike covers.

Currently, dikes are designed on the basis of long time experience, specific physical models and analytical approaches. In this context, various technical guidelines do exist (e.g. EAK (2002), International Levee Handbook (CIRIA, 2013), TAW (1996)).

Specific aspects concerning dike resistance (e.g. crack development, influence of the grass revetment on the erosion resistance, erosion of the dike material) are examined independently in numerous research projects. A holistic design approach is currently missing.

In this context, a research project at the Federal Waterways Engineering and Research Institute in Hamburg (BAW Hamburg) is carried out. Here, studies on existing dikes as well as on test dikes are conducted, to analyse the influence of soil formation processes on the dike persistency (Fig. 1). Undisturbed soil samples are taken at dikes of different ages. Field and laboratory experiments are carried out. Prior to sampling, water is infiltrated into the dike cover to simulate the exposure of the dike to high water levels. Due to the infiltration the water content of the dike cover is changed. Various soil-mechanical parameters are determined by field and laboratory methods, some with the regard to the in situ water content.

The results are used as input parameters for a holistic numerical model using the Software FLAC3D where different modell layers (e.g. glacial till and dredged material) can be defined. Specific soil-mechanical characteristics can be assigned to those model layers. Since FLAC3D is a coupled mechanical-hydraulic model specific dike-characteristics (dike material, soil structure) under the influence of hydraulic events (e.g. storm surge, wave attack) can be analyzed within the simulations. Using a numerical model, failure mechanisms can develop freely and the superposition of various factors can be examined.

In autumn 2011 infiltration tests and soil-sampling were conducted at two existing dikes at the Baltic Sea Coast in Dahme, Schleswig-Holstein with the permission of the responsible authorities (LKN – Schleswig-Holstein). The first dike (the so-called old dike) was subsequently heightened in the past from the 1860ties on. The upper layer is several decades old. Constructions of the second dike (new dike) were just finished. Both dikes are constructed of homogenous glacial till. The old dike is covered with a well grown grass revetment. Both dikes have a typical geometry for the Baltic Sea region. The height of the dikes is approx. 5 m above sea level. The sea-side slopes are 1:6 to 1:9 and at the landside 1:3.

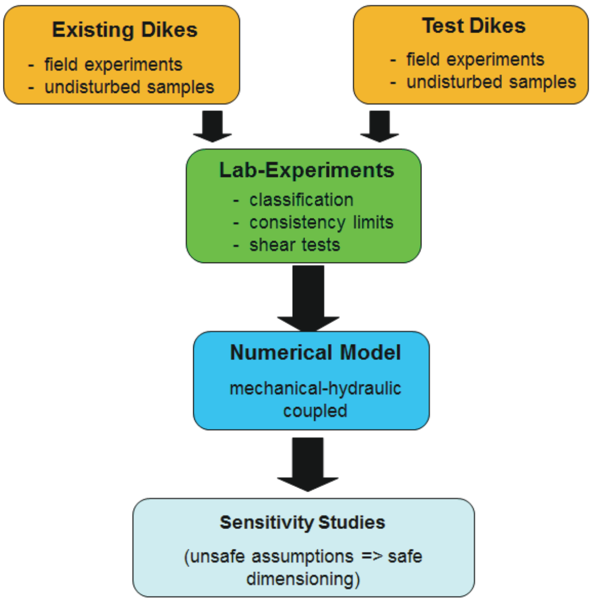

Fig 1. Study approach

Fig 2. Soil sampling

In this paper the first results of a sampling campaign carried out in 2011 are presented. In autumn 2013 further tests were performed. The examination and laboratory tests are currently going on. Additionally, an overview of the modelling approach and how the results will be implemented in the numerical model is given.

2. Methods

2.1 Soil-sampling

At both dikes two representative sampling-areas are chosen on top of the dike crown. At every of those sampling-areas undisturbed soil-samples were taken at three different spots using a conventional drilling rig (Fig. 2). At every spot undisturbed soil samples were taken at different depths (25 cm, 55 cm, 85 cm, 115 cm and 150 cm below surface).

Since there was no rainfall several weeks before the sampling, the sampling took place under dry conditions. At one sampling point water was infiltrated for 4 hours prior to sampling. At the second sampling point water was infiltrated for 14 hours, and at the third spot there was no infiltration (so-called dry sample). With this approach the exposure of the dike to high water levels with a different duration are simulated. The samples were taken in the center of the infiltrated areas. The sampling points had a sufficient distance to exclude interacting effects. (Note: In 2013 the samples were taken in a period of heavy rainfall, so that the influence of the infiltration can be determined.)

With the dry drilling method borehole-diameters of 219 mm are executed, so that sampling tubes with a diameter of 114 mm and a length of 25 cm could be gained. After sampling the boreholes were closed adequately.

2.2 Infiltration Tests (On-site)

The potential infiltration rates into the dike covers are measured with a double ring infiltrometer according to the German Standard DIN 19682-7. The double ring infiltrometer is a simple instrument to measure the water infiltration of soils. Two rings with defined diameters are arranged as an inner and an outer circle. They are partially inserted into the dike cover and filled with water.

Using a measuring rod with floats the water level within the inner ring is measured over time. Using a double ring the lateral spread of water after the infiltration is limited. The infiltration rate is expressed in terms of the volume of water per ground surface and per unit of time (mm/s).

2.2 Laboratory Methods

Examining the soil samples the following laboratory methods are carried out at the soil-mechanical-laboratory of the BAW in Hamburg:

- grain size distribution
- water content
- consistency limits (liquid limit and plastic limit)
- initial shear strengths using a pocket penetrometer
- effective shear-strengths by triaxial tests
- oedometer tests
- lime content

The effective shear strengths of the soil samples are determined by triaxial shear tests. Here, consolidated drained (CD) tests are conducted in which the water content of the samples is used which resulted out of the on-site infiltration tests (i.e. no back-pressure was applied). The consolidation stress was chosen to 10 – 30 – 60 kPa to simulate the on-site conditions realistically. With this approach the effective shear parameters c' and φ' for field conditions are determined as well as the stress-strain-curves for the numerical model. For the constitutive law of the model also oedometer tests are performed. Here, also the "natural" water content of the soil-samples was used.

3. Results

3.1 Infiltration tests

In Fig. 3 the results of the on-site infiltration tests are shown. For the old dike the measured infiltration rates are between $1*10^{-6}$ and $5*10^{-5}$m/s. The new dike shows infiltration rates lower than $5*10^{-6}$ m/s. These infiltration rates are lower than the results for dikes with clayey marsh soil covers at the German North Sea coast published by Temmler (2007) and TAW (1996).

Apparently the infiltration rates of the old dike are higher because of the impacts of periodically reoccurring soil wetting and drying processes as well as freezing and unfreezing. Shrinkage cracks as well as holes by burrowing animals (earthworms) also occur, which result in an increase of the permeability with time (TAW, 1996; Weißmann, 2003, Pohl, 2010).

3.2 Visual inspection of the soil samples

In fig. 4 and 5 undisturbed samples of the new and the old dike are shown. The samples of both dikes show heterogeneous material, whereas the material of the old dike seems to be more decomposed.

At the new dike there is a clear boundary between the raw glacial till and the zone where the top soil is remoulded. Also lime can be seen in the sample. It is obvious, that for the interpretation of the results the heterogeneity has to be taken into account. Because of the low number of examinations so far, it is difficult to quantify the effects due to the heterogeneity at this state of the project. Therefore, the here presented results are to be understood as first results. Future examinations to validate those first results are required.

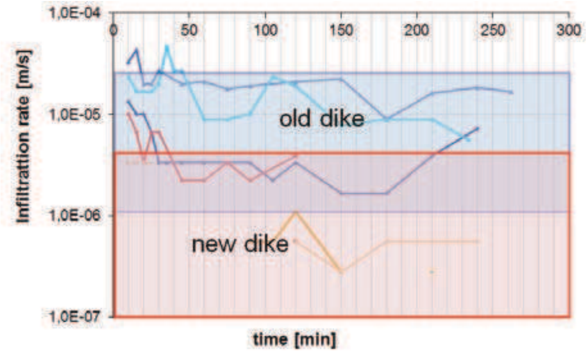

Fig 3. Results of the infiltration tests


Fig 4. Undisturbed sample of the old dike (0 – 0.25 m)


Fig 5. Undisturbed sample of the new dike (depth 0 – 0.25 m)

3.3 Water content, liquidity and initial shear strength

The strength of cohesive soils depends on its water content. This is proven by numerous investigations including dike covers made out of clay. In this context the interrelations between consistency, the water content and the initial shear strength is analysed.

The liquidity index L_I describes the condition of a remoulded soil regarding the actual water content w_L and defined consistency limits (liquid limit w_L and plasticity limit w_P) . The liquidity index is defined as:

$$L_I = \frac{w - w_P}{w_L - w_P}$$

The old dike and the new dike show relatively high L_I-values. The liquidity of the old dike is higher than of the new dike. The liquidity indexes of the samples taken at a depth of 0.25 m are decreasing with the infiltration duration i.e. the soil softens.

Comparing the water contents measured for the old dike over the sampling depth (Fig. 6), the effects of the infiltration can be seen down to a depth of 0.25 m below surface. The “dry” samples show a range between 10 and 17 %, the infiltrated samples between 17 and 32 %.

Effects of the infiltration can also be seen at the initial shear strengths c_U (Fig. 7). The values of the samples exposed to a 4h infiltration are much lower than the values of the dry samples. Besides that, the initial shear strengths seem to decrease with depth under dry conditions.

As expected, the determined initial shear strengths of the samples show a correlation to the water content. This observation can be made for the samples taken out of the old dike as well as for samples taken out of the new dike (Fig. 8).

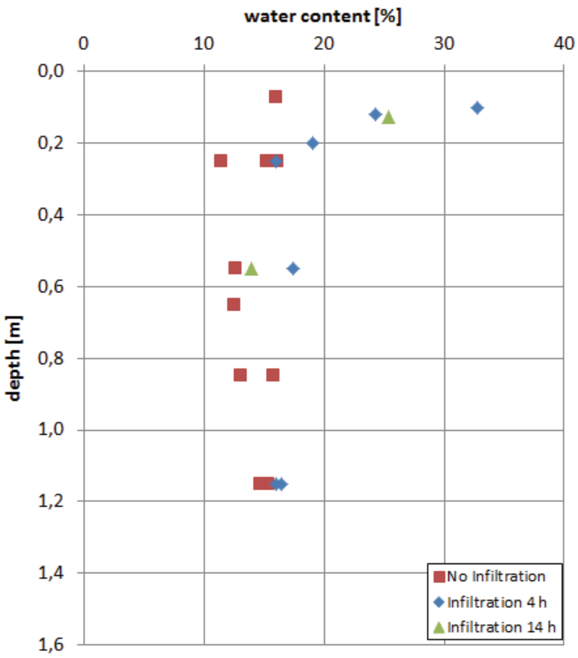

Fig 6. water content over depth (old dike)

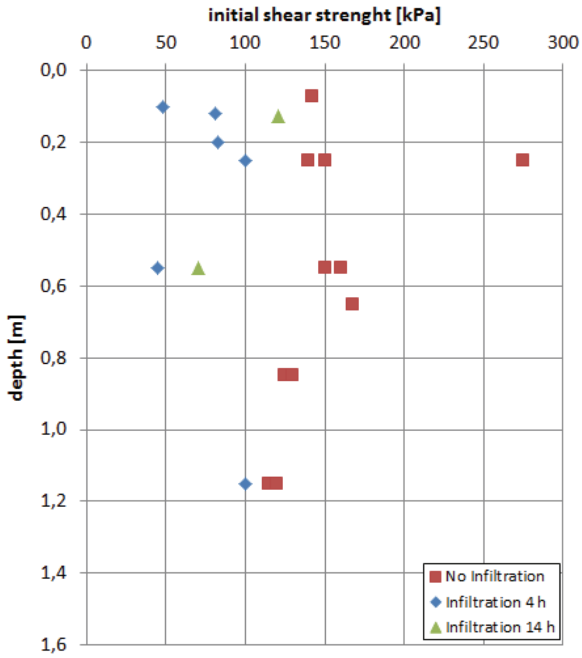

Fig 7. Initial shear strength over depth (old dike)

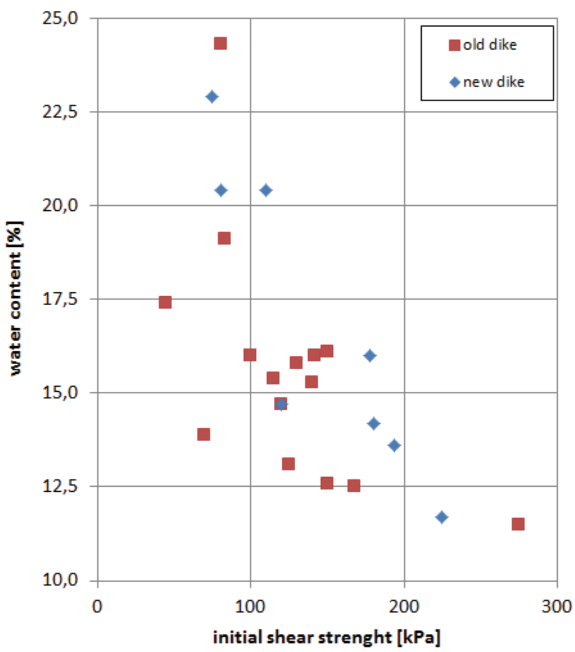

Fig 8: water content over initial shear strength (both dikes)

For the old dike the results signify more heterogeneous conditions, since the distribution of the values implies a wider range. Also, there seems to be a tendency that the samples of the new dike have higher initial shear strengths at comparable water contents. As already mentioned above, more investigations are needed, to validate these first observations concerning the correlation between the water content and the initial shear strength.

According to the EAK a minimum c_U-value of 20kPa due to compaction is required for the use of cohesive materials as a dike cover. Since all of the measured c_U-values are above 40 kPa the used material fulfils that recommendation.

3.4 Lime content

Since the lime content of a soil increases the shear strength, the correlation between the lime content and the initial shear strenght is evaluated (Fig. 9). Because of aging and elution processes, the lime content of the samples taken at the old dike are comparatively low. In spite of those low lime contents high c_u-values are measured at samples of the old dike. There's no correlation between those two parameters. This observation has to be further examined.

The samples of the new dike show higher values and a wider range of measured lime contents. Here, a correlation between the lime content and the initial shear strength can be assumed.

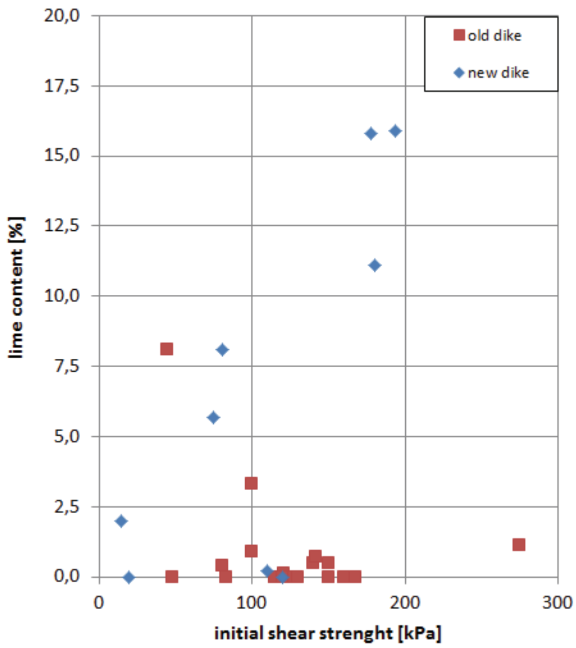

Fig 9: initial shear strength over lime-content

3.5 Clay content and Activity index

Fig. 10 illustrates the clay content over depth for the old and the new dike. In the upper zone of the old dike the clay content is half as low as in its lower part. The clay contents of the upper zone of the new dike show nearly the same amount as in the lower part of the old dike. One possible explanation is that material transport through cracks and fissures into the lower zones of the dike cover took place in the old dike.

Different types of clay minerals have different specific surface areas and different cations and water absorption capacities (Scheffer and Schachtschabel, 2010). These factors are relevant for the soil-properties in terms of its consistency limits and initial shear strenghts.

According to Skempton (1953) the activity of a soil is defined as the ratio between the plasticity index to the clay fraction (particles<2 μm). Based upon the activity index, the dominant clay-mineral in a soil sample can be estimated. High activity signifies a large volume change when wetted and large shrinkage when dried. Soils with a high activity are chemically very reactive. Normally the activity of clay is between 0.75 and 1.25. When the activity index is less than 0.75 it is considered inactive. When it is greater than 1.25 it is considered active. An activity index between 0.5 and 1 indicates Illit as the dominant clay mineral, values above 1 are typical for Montmorillonite respectively Smectites (Mitchell, 1993).

Activity indexes over depth are illustrated in Fig. 11. For the old dike the activity of the clay decreases with depth. According to the classification after (Mitchell, 1993) Smectites are present in the upper zone, whereas Illits are dominating the lower areas of the old dike. Assuming that the dike was constructed more or less homogenous in terms of its clay-mineral composition, soil-formation processes must have taken place. In the future, investigations regarding the clay-minerals will be done in detail.

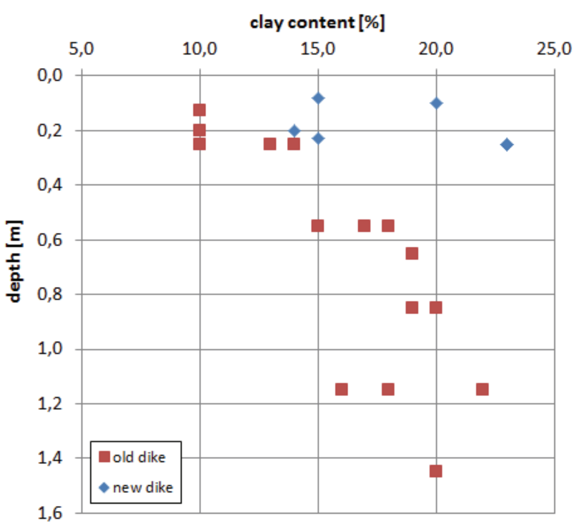

Fig 10: Clay content over depth (both dikes)

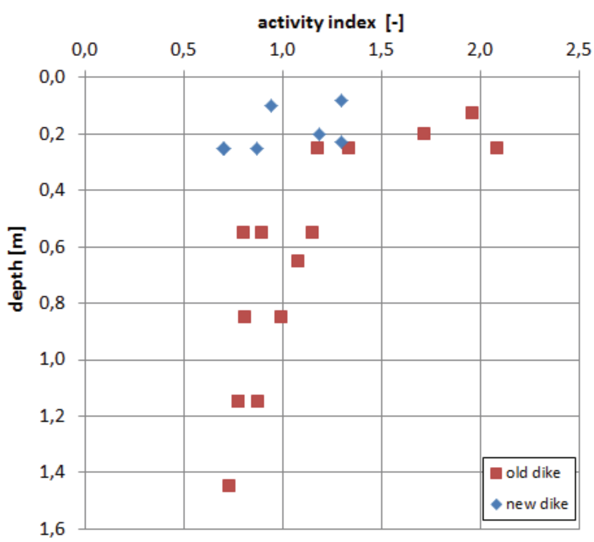

Fig 11. Activity index over depth (old dike)

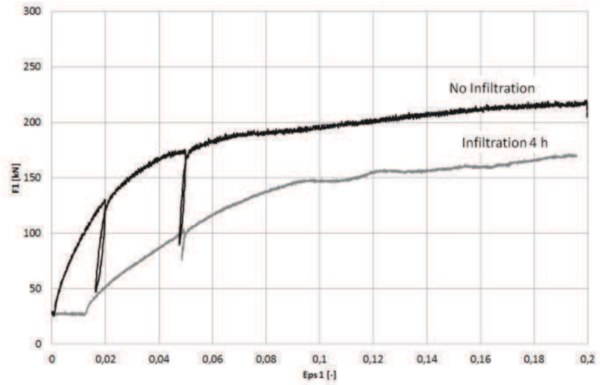

Fig 12: strain-stress curves of samples with different infiltration durations (old dike)

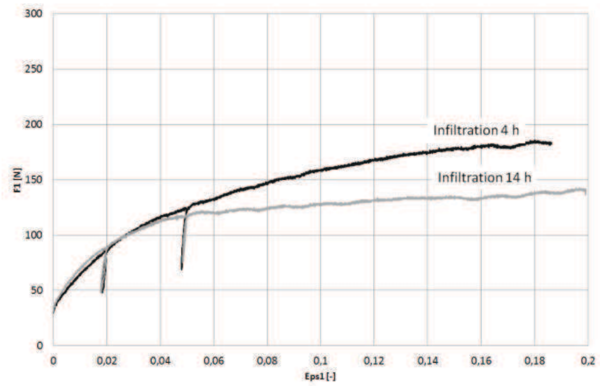

Fig 13: strain-stress curves of samples with different infiltration durations (new dike)

3.6 Stress-strain behaviour

So far, only a few samples have been examined regarding the stress-strain-behaviour. Evaluating all available stress-strain-curves a correlation between the water infiltration and the strain-stress-behaviour cannot be stated clearly. Here, effects of the heterogeneity of the dikes may superpose the effects of the water infiltration.

Regarding selected stress-strain curves, gained at samples taken in the upper 0.25 m of the old and of the new dike (Fig. 12 and Fig 13) indicate the effects of the infiltrations, though. Unfortunately, a stress-strain curve of a dry sample of the new dike has not been examined so far. Here, again more examinations are needed to validate the correlation between the water infiltration and the stress-strain-behaviour.

4. Numerical Modelling - Approach

The crucial component of the holistic approach is the numerical model using the Software FLAC3D 5.0 (ITASCA, 2009). FLAC3D is a numerical modelling code for advanced geotechnical analysis of soil, rock, and structural support in three dimensions. Due to the complexity of a dike, an appropriate modelling approach requires a wide range of model features. In this context FLAC3D was chosen for the following reasons:

- FLAC3D is using an explicit solution scheme, so stable numerical solutions to unstable physical processes are possible.
- Large strain simulations with interfaces or slip-planes are also possible, so that the presence of faults, joints or frictional boundaries which occur in a dike (e.g. grass revetment) can be simulated.
- Structural elements (e.g. sheet-pile walls) that interact with the surrounding soil can be included in the model.
- FLAC3D allows the simulation of fully coupled mechanical-hydraulic interactions as well as the modelling of time-dependent processes.
- Material properties can be assigned to different model layers considering field and laboratory results as presented in this paper. Also statistical distributions of any parameter can be specified, so that heterogeneous soil properties of a dike can be analysed by various simulation runs.

So far, the dike model is set-up in FLAC3D. Further, the strain-stress-diagrams are included into the model. At present, test simulations with the dike model are carried out.

5. Discussion and Conclusions

Because of the low number of examinations, the above described results have to be taken as first findings. Future examinations are needed to validate these first results. Based upon this first sampling campaign further aspects will be examined in detail, namely the clay-mineral composition of the dike and the cation distribution of the clay minerals.

The examinations made so far indicate the following results:

1. The older dike shows higher infiltration rates than the newly constructed dike due to various processes. Consequently the water content of the infiltrated zones is higher in the old dike than in the new constructed dike.
2. At the old dike the initial shear strengths, the plasticity, the liquidity and the activity of the clay minerals are higher in the first 25 to 50 cm than in the lower part of the dike. Further, the dike cover material of the new dike seems to be characterized by higher initial undrained shear strengths at the same water contents. At the old dike the influence of the lime content on the shear strength is not significant. In this context further investigations regarding the interaction between the various factors need to be done.
3. A clear correlation between the water content and the stress-strain-behaviour is currently not possible. The heterogeneity of the dikes may superpose the effects of the water infiltration. A few selected stress-strain-curves show a slight correlation, though. More examinations are needed.
4. Apparently, cracking and fissuring processes as well as mechanical, transport and soil-formation

processes (e.g. compaction, agglomeration, reformation of the structure of clay minerals) which influence the mechanical persistency and the permeability occur at the same time.

5. Soil formation processes, particle-transport and reformations of clay-minerals take place. Consequently the dike cover changes its different properties regarding their wetting and drying capability and their ion composition with time.

It is planned to accompany the new constructed dike in Dahme over the years, to confirm and to verify the here presented findings. Also, the examination approach will be adapted continuously to the findings.

Besides field and laboratory experiments on the existing dikes, investigations at experimental dikes are planned for the future. Dredged materials from German federal water ways will be used for the dike cover as an alternative to the common construction materials.

Besides the findings discussed above, the results of the sampling campaign show that a dike is a complex, heterogeneous structure. Since a dike is exposed to permanently changing conditions it changes its properties over time. Also, the different factors interact in very complex matters. Obviously, the geotechnical dimensioning of dikes requires more than calculations under steady state conditions or examinations of various influencing factors which are done independently. A holistic approach is needed e.g. based upon a numerical model in which specific dike characteristics (dike material, soil structure,) under the influence of hydraulic events (e.g. storm surge, wave attack) can be analysed. With this approach, dike damage and potential risk areas can be determined by a parameter variation.

With the numerical modelling approach the use of dredged material solely but also in combination with other cover materials can be examined. Here, sensitivity analysis based upon measured soil mechanical parameters can be done. Additionally, it will be possible that geotechnical aspects of planned dredged dikes can be examined and compared to existing dikes. Hence, the suitability of dredged material for a dike construction can be proven easily. Therefore, dikes can be dimensioned economically on the basis of simulation results. With this approach a holistic examination or dimensioning of existing and planned dikes will be possible.

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