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A Comprehensive Numerical Approach for Stability Analyses of German Sea-Dikes

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Abstract: Dikes along German coastlines are designed primarily based on long term experience, physics-based limit state models and analytical approaches. When analyzing the stability of these dikes, various technical codes and standards have to be considered. Hence, specific aspects regarding failure mechanisms and materials are examined independently. However, identification of weak points and failure mechanisms require a comprehensive approach. In this context a three-dimensional numerical model using the software FLAC3D was developed. This model is based on examinations of different dike covering materials. Samples were taken at various dikes and geotechnical lab experiments were conducted. The results of these tests are used as input parameters for the constitutive model in the numerical analyses. For some materials (glacial marl) the determination of the exponent m – which is crucial for the formulation of the stiffness modulus E\textsubscript{s} within the chosen hardening soil model - show results which differ from common assumptions. Here, values for m between 0.54 and 0.86 were determined. Using those parameters the vertical deformations calculated with the model correspond to the subsidence on the shore-side of the dike and to the small uplift of the covering layers. Comparing the deformations obtained from the different dike covering materials, there seems to be a correlation between the magnitude of the deformation and the permeability.

Keywords: Sea-dikes; soil-mechanical tests; numerical model; finite difference; constitutive model.

1 Introduction

For the protection of the German coastlines, sea-dikes play an important role. As a result of numerous historic storm surges, the design of German sea-dikes has improved over the centuries. Modern sea-dikes are characterized by a sophisticated geometry consisting of a sand core with a covering layer which is usually made out of cohesive material, such as marsh clay at the North Sea coast or glacial marl at the Baltic Sea coast. Due to climate change, a rise of the seawater level as well as more frequent occurrences of severe storm surges is expected. Also, scarcities of the cohesive materials as well as legal issues regarding the winning of the material are arising. Therefore, the use of alternative materials such as dredged materials is in discussion. The design of the German sea-dikes is still based on long term experience, on physics-based limit state models and analytical approaches (e.g., EAK 2002, CIRIA 2013, TAW 1996). However, modern assessments of existing dikes as well as the design of new sea-dikes require a more comprehensive approach. In this context a three-dimensional, numerical dike model using the software FLAC3D is developed. The software FLAC3D (ITASCA 2013) is a widespread finite difference numerical modeling program for advanced geotechnical analysis of soil, rock, and structural support in three dimensions. Due to the complexity of a dike, an appropriate modeling approach requires a wide range of model features. In this context FLAC3D was chosen since it is using an explicit solution scheme. Hence, stable numerical solutions to unstable physical processes are possible. Also, large strain simulations with interfaces or slip-planes are possible, so that the presence of frictional boundaries which occur in a dike (e.g., grass revetment) can be simulated. Furthermore, the simulation of fully coupled mechanical-hydraulic interactions as well as the modeling of time-dependent processes is allowed. Thinking of wave attack at sea dikes, this is of high importance. Using FLAC3D coupled mechanical-hydraulic processes in a dike can be simulated. Specific dike-characteristics (dike material, soil structure, etc.) under the influence of hydraulic events (storm surge, wave attack) can be analysed. Also, dike damage and potentially high risk areas can be determined through parameter variation, and coastal protection measures can be evaluated. The model is based on examinations of different dike covering materials. Undisturbed soil samples were taken at several dikes along the German coastlines, numerous laboratory tests were conducted in order to gain a suitable database for the input parameters for the constitutive model in the numerical analyses. The objective of this paper is to describe the setup of the model as well as the selection of the constitutive model and the parametrization according to the results of the field- and laboratory investigations.

2 Geotechnical Investigations

2.1 Sample sites

For the determination of representative soil parameters undisturbed soil samples were taken at two study sites. The first site is in a small town called Dahme, which is located at the Baltic Sea. The second site is Bremen-Farge, representative for typical conditions of the German North-Sea coast. In Dahme, samples were taken at two different dikes. Both dikes are constructed of glacial marl, and their geometry is typical for the Baltic Sea.
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The heights of the dikes are approx. 5 m above sea level. The sea-side slopes are 1:6 to 1:9, and the landside slopes are 1:3. The so called “old” dike (figure 1, left) was constructed in the 1860s, and it was subsequently heightened over time. The upper “newer” layer is already several decades old and is covered with a well grown grass revetment. The second dike in Dahme, referred to as the “new” dike was constructed before sampling in the year 2010. The dike in Bremen-Farge is characterized by a steeper slope on the shore-side. It is constructed with a sandcore and a covering layer existing out of a dredged material layer topped with a layer out of marsh clay (figure 1, right).

Figure 1. Cross sections of the “old” dike in Dahme (left) and the dike in Bremen-Farge (right)

2.2 Sampling technique
At every study-site water is infiltrated into the dike cover to simulate the exposure of the dikes to high water levels prior to sampling. At each dike, two representative sampling-areas are chosen on top of the dike crown, where undisturbed soil-samples were taken at three different spots using a conventional drilling rig. Here, undisturbed soil-samples were taken at different depths (25 cm, 55 cm, 85 cm, 115 cm and 150 cm below surface). Borehole-diameters of 219 mm are realized so that sampling tubes with a diameter of 114 mm and a length of 25 cm were taken. After sampling the boreholes were closed adequately.

2.3 Field- and lab-tests
Besides on-site infiltration tests according to the German Standard DIN 19682-7 numerous experiments with the soil samples are conducted at the soil-mechanical-laboratory of the BAW in Hamburg, Germany. Here, grain size distribution, water content, consistency limits (liquid limit and plastic limit), undrained shear strengths by penetrometer tests, effective shear-strengths by triaxial tests, and oedometer tests were pursued. The effective shear strengths of the soil samples are determined by triaxial shear tests. Consolidated drained (CD) tests are conducted, where the water content of the samples resulting out of the on-site infiltration tests is used. The consolidation stresses were chosen to be 10–30–60 kPa to simulate the on-site conditions realistically. With this approach, the effective shear parameters $\phi'$ and $c'$ for field conditions are determined. The stress-strain-curves resulting out of the triaxial tests were also used for the selection of appropriate model parameters that yield similar stress strain characteristics. stress-strain-curves for the numerical model are determined. Also, oedometer tests are performed for the constitutive model parameters. Based upon the results of the oedometer tests, the reference odometer modulus ($E_{\text{ref}}$) is derived, to control the magnitude of the plastic volumetric strains.

2.4 Results
The results of different sampling campaigns are partially published in Nuber and Pohl (2014). For the “old” dike in Dahme 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 rates for clayey marsh soil covers at the German North Sea coast published by Temmler (2007) and TAW (1996). Apparently the higher infiltration rates of the “old” dike in Dahme are caused by 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; Pohl 2010). Figure 2 shows the plasticity diagram according to Casagrande including the results of all examined dike covering materials. The samples of the glacial marl can be characterized by a low plasticity, whereas the marsh clay and the dredged material show a higher plasticity. According to Langer (1963) as well as to the EAK 1993 – in which specific requirements for the use of dike covering materials are defined – all of the samples are suitable for the use as dike covers (figure 2).
As shown in figure 3 the shear-strengths, water contents as well as the stress-strain behavior of the examined dike covering materials differ significantly. Also, the dependency of the undrained shear-strength on the water content can be observed. The “natural” materials show a similar range and a relation of the water content and the undrained shear-strength. Despite the higher water content the samples of the dredged material cover almost the same range of the undrained shear-strength as the other materials. Also, the samples of the glacial marl show a higher stiffness. Regarding the cover material requirements formulated in the EAK all materials are eligible for the use as dike covering materials, whereas they show significantly different properties. To adequately describe these differing soil behaviors in the numerical model, an elasto-plastic constitutive model which is capable of representing the soft soils will be used.
3 Numerical Analyses

3.1 Software

3.1.1 Hydraulic-mechanical coupling
The quasi-static theory of poroelasticity where the interaction of stress in a grain skeleton and pore pressure due to interspace fluid in a porous media is considered (Biot 1941). The calculation is performed in two continuously consecutive running loops. At first the pore pressure is calculated in the flow loop followed by the mechanical loop, where the volumetric strain of the material due to the calculated pore-pressure is determined. Within this loop, the effective stress resulting out of the pore pressure and volumetric strain is applied to the gridpoints.

3.1.2 Constitutive models
The properties of the dike cover materials require elasto-plastic constitutive models. Therefore the CYSoil-model and the Strain-Hardening / softening - models were used in an earlier stage of the project. Problems occurred using the CYSoil and Strain-hardening/softening – models as described in Sorgatz and Nuber (2017). Hence, further model runs were done using the plastic hardening-soil model which was implemented in FLAC3D version 6.0. This constitutive model is based on the work of Schanz et al. (1999) who extended the hyperbolic non-linear elastic model in an elastic framework to provide a more realistic pre-failure stress-strain-behaviour. Also the yield surface is not fixed in the principal stress space. Instead it can be expanded as a function of plastic strain; this yield surface behavior is referred to a plastic strain hardening.

3.2 Dike model

3.2.1 Geometry, initial and boundary conditions
For a fast Set-up of different dike geometries, a special tool – the so called dike-generator – was developed. With this tool the spatial discretization and the necessary input files can be generated. The dike exists out of three underlaying layers, a dike core and a covering layer. Also, different heights and slopes can be defined using this tool. For the first model runs the geometry of the dike-models is designed in accordance to typical sea-dikes at the German North Sea coast.

Mechanical boundary conditions are applied to the models edges on the shore-side, the land sides and the bottom of the model. Hydraulic boundary conditions were applied at gridpoints on the shoreside which are exposed to water and at the gridpoints at the outer edge of the landside. Here, in the equilibrium state a steady-state flow through the dike occurs. By rising or declining the pore-pressures at the water exposed shore-side gridpoints, tides and storm surges can be simulated in order to perform hydraulic transient simulations. So far, a wave attack can only be simulated in a simplified manner.

3.2.2 Parametrization
The selected plastic-hardening model requires various parameters. Here, crucial parameters are the friction angle $\phi'$, cohesion $c'$ and the $E_{50}$ stiffness. As described in section 2.3 numerous consolidated triaxial compression tests were performed. For each material the friction angle $\phi'$ and cohesion $c'$ is derived from the correlation of the deviatoric stress $q$ with the normal stress $p$ as shown exemplary in figure 4 (left).

The dependency of the stiffness parameters on a general state of stress is a fundamental characteristic of the plastic hardening model. The plastic-hardening model also employs another stiffness parameter, $E_{50h}$, which defines the shape of the primary shear hardening surface and takes the following power law (Schanz 1999):

$$E_{50} = E_{50h} \left( \frac{c \cdot \cot \phi + \sigma_3}{c \cdot \cot \phi + p^{cr}} \right)^m$$

The relationship between the $E_{50}$ modulus and the effective confining stress $\sigma_3$ is influenced by the exponent $m$. Usually for cohesionless materials the exponent $m$ is in a range of 0.4 and 0.55. For cohesive materials, the exponent $m$ is controversial (Benz 2007). As shown in figure 4 (right), values of the $E_{50}$ modulus obtained from the triaxial tests are related to the corresponding confining pressure $\sigma_3$. Based on the result of 40 triaxial compression test, $m$ was determined to be in the range between 0.54 and 0.86 for the glacial marl (Dahme). The undisturbed soils samples were collected from a depth of 0–2 m below the dike crown. The confining pressure ranged from 10 to 60 kPa. The other parameters were also derived from the conducted field and laboratory test. The chosen parameters for the different dike covering materials are summarized in table 1 and table 2. The values of the parameters, which derived from laboratory results, was calibrated by analysis in FLAC 3D.
Figure 4. Determination of friction angle $\phi$ and cohesion $c'$ for the glacial marl (left); Determination of exponent $m$ and $e^{\gamma m}$ for the glacial marl from three sets of triaxial test (right)

Table 1. Hardening Soil Model parameters sets

<table>
<thead>
<tr>
<th>Parameter Description</th>
<th>gl marl (old)</th>
<th>gl marl (new)</th>
<th>dredged mat. marsh clay</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_{50-ref}$ [MPa]</td>
<td>2.11</td>
<td>5.44</td>
<td>1.83</td>
</tr>
<tr>
<td>$E_{oed-ref}$ [MPa]</td>
<td>32.06</td>
<td>38.92</td>
<td>24.13</td>
</tr>
<tr>
<td>$E_{ur-ref}$ [MPa]</td>
<td>32.06</td>
<td>38.92</td>
<td>24.13</td>
</tr>
<tr>
<td>$e_p$</td>
<td>0.59</td>
<td>0.86</td>
<td>0.80</td>
</tr>
<tr>
<td>$\phi$</td>
<td>35.50</td>
<td>32.40</td>
<td>30.40</td>
</tr>
<tr>
<td>$c'$</td>
<td>8.40</td>
<td>21.20</td>
<td>12.30</td>
</tr>
<tr>
<td>void init [-]</td>
<td>0.31</td>
<td>0.32</td>
<td>0.47</td>
</tr>
</tbody>
</table>

All parameters were obtained from the triaxial tests

* this material need to be calibrated more triaxial test data

Table 2. Constitutive model parameters sets

<table>
<thead>
<tr>
<th>Parameter Description</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\gamma$</td>
<td>Internal friction angle</td>
</tr>
<tr>
<td>$\phi$</td>
<td>Cohesion</td>
</tr>
<tr>
<td>$R_f$</td>
<td>Failure ratio</td>
</tr>
<tr>
<td>$\psi$</td>
<td>Dilatancy angle</td>
</tr>
<tr>
<td>$E_{triax}$</td>
<td>Reference secant stiffness from drained triaxial test</td>
</tr>
<tr>
<td>$E_{oed}$</td>
<td>Reference secant stiffness from for oedometer primary loading</td>
</tr>
<tr>
<td>$E_{ur}$</td>
<td>Reference unloading /reloading stiffness</td>
</tr>
<tr>
<td>$m$</td>
<td>Exponential power</td>
</tr>
<tr>
<td>$n$</td>
<td>Poisson’s ratio</td>
</tr>
<tr>
<td>$K_o$</td>
<td>Coefficient of earth pressure</td>
</tr>
</tbody>
</table>

4 Conclusions and Outlook

The plastic-hardening model was used, and the parametrization according to the results of the field and laboratory experiments was carried out. Also, the tidal influences were simulated. With this approach the calculated hydraulic heads show an expected distribution (figure 5, left). The calculated vertical deformations (figure 5, right) correspond to the subsidence on the shore-side of the dike and to the small uplift of the covering layers. Comparing the deformations obtained from the different dike covering materials, there seems to be a correlation between the magnitude of the deformation and the permeability.

According to the results the principal hydraulic and mechanical behaviour of a dike can be simulated. In this context it is planned to regard the material parameters as a function of the water saturation and of the dike’s age. Also, erosion processes of the dike covering layers will be considered by coupling the model with distinct element method models (DEM), so that the consideration of erosion processes under wave attack is possible. It is recommended that the calibration of the parameters be carried out to obtain a more accurate prediction of the behavior of DEM using cohesive materials. Finally, specific dike-characteristics (dike material, soil structure, etc.) under the influence of hydraulic events (storm surge, wave attack) are to be analyzed for the expected sea level rise by climate change.
Figure 5. Hydraulic heads (right) and vertical deformations (left) for glacial marl dike

References