INTERACTION OF WAVE OVERTOPPING AND CLAY PROPERTIES FOR SEADIKES

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Abstract: The interaction of wave overtopping and the soil properties of a seadike is responsible for the initiation of dike failures and the breaching process. Unfortunately, the present design of seadikes is based on the separate determination of hydraulic and geotechnical design parameters. Therefore, large scale hydraulic model tests were set-up on the basis of a detailed failure analysis for seadikes to investigate the infiltration and erosion process due to wave overtopping. Results are presented in this paper.

INTRODUCTION

Dike failures are often initiated by wave overtopping (Fig. 1). If a broken wave overtops a dike crest, the overtopping water is eroding the dike surface and water is infiltrating the soil. Therefore, the knowledge about the interaction between the hydraulic processes due to wave overtopping and the soil properties is required to predict the failure of a seadike. Unfortunately, the design of seadikes is performed in two separate ways in present design. First, the crest level is determined by a design water level and the resulting wave run-up height. Sometimes, an average overtopping rate is regarded and compared to critical

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overtopping rates. The Dutch guidelines (in Van der Meer et al., 1998) recommend the following allowable average overtopping rates for the inner slope of a seadike:

Fig. 1. Total Dike break on the island of Romo /Denmark(photo: Piontkowitz)

- 0.1 *l*/(sm) for a sandy soil and poor grass
- 1 *l*/(sm) for a clayey soil with a relatively good grass
- 10 *l*/(sm) for a clay protective layer

These allowable average overtopping rates are rough estimates, whereas a determination of an allowable overtopping rate based on the exact soil and grass properties is missing. In a second step, the geotechnical stability of a dike is determined by different calculation methods (e.q. wedge method, Bishop method, etc.). Nevertheless, wave overtopping is not considered directly in these methods.

Therefore, a calculation method is required which takes into account the interaction process between wave overtopping and soil properties.

A research project was initiated in Germany to investigate this interaction process (Fig. 2). In a first phase, dike failures in the past were reviewed and the main failure mechanisms were described. Then, typical dike geometries and soil conditions of German seadikes were classified. In addition, measured wave spectra from the North Sea (wadden sea, foreland areas, etc.) were collected and classified. The collection of all these data was necessary to ensure that typical site conditions were regarded during the project. In a second phase, theoretical investigations, experiments (small and large scale), laboratory investigations and numerical modeling were performed to get information about the overtopping flow properties and the soil properties. In a third phase, all data were analyzed to describe (i) the overtopping flow parameters on the dike crest and the inner slope (Schüttrumpf et al., 2002), (ii) the influence of natural wave spectra on wave run-up and wave overtopping (Schüttrumpf et al., 2001), (iii) the interaction process between wave overtopping and soil properties and (iv) to develop a concept for dike failures. Objective of this paper is the description of the interaction between wave overtopping and the soil properties.

In the following, the main results of the failure analysis are given to compare observations in nature to the experiments. Afterwards, model set-up and test program of the large scale model tests are described. Finally, the main observations from the large scale experiments are described and interpreted.

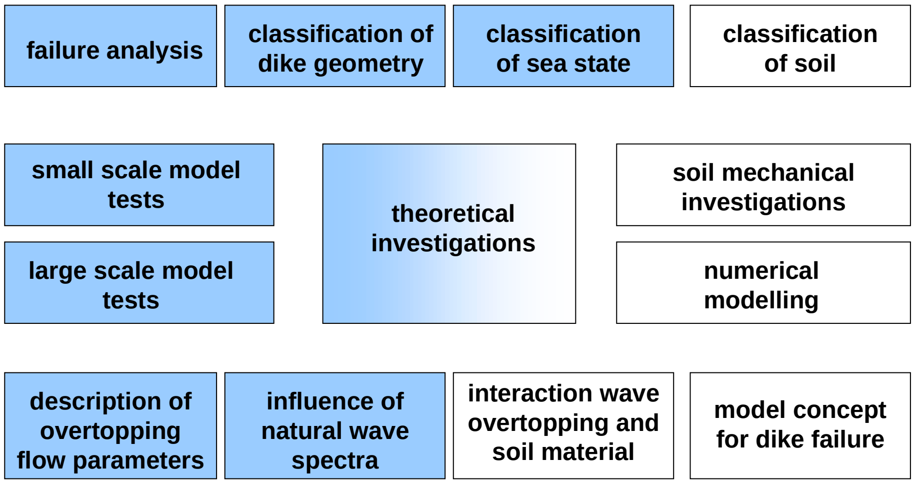


Fig. 2. Methodology

FAILURE ANALYSIS

Many dike failures occurred in the last centuries due to wave overtopping. First information on dike failures due to wave overtopping are available for a storm surge in 1825 which caused many dike breaks. Detailed information on dike failures due to wave overtopping are available for the storm surge in 1953 which caused about 1850 fatalities in the Netherlands, the strom surge in 1962 which caused about 340 fatalities in Germany and a storm surge in 1976 which caused no fatalities but flooded many areas in Germany.

Causes for Dike Failures

The analysis of dike failures in the past shows, that dike failures occurred in combination of wave overtopping and one or more other critical circumstances like critical meteorological conditions (e.g. rain, dryness, etc.), non-adapted dike geometry (e.g. low crest level), unsufficient soil properties (e.g. high percentage of sand), flotsam, bad maintenance or negative biological conditions (e.g. trees, voles, etc.). Nevertheless, the main cause for a dike failure on the inner slope is the overtopping process.

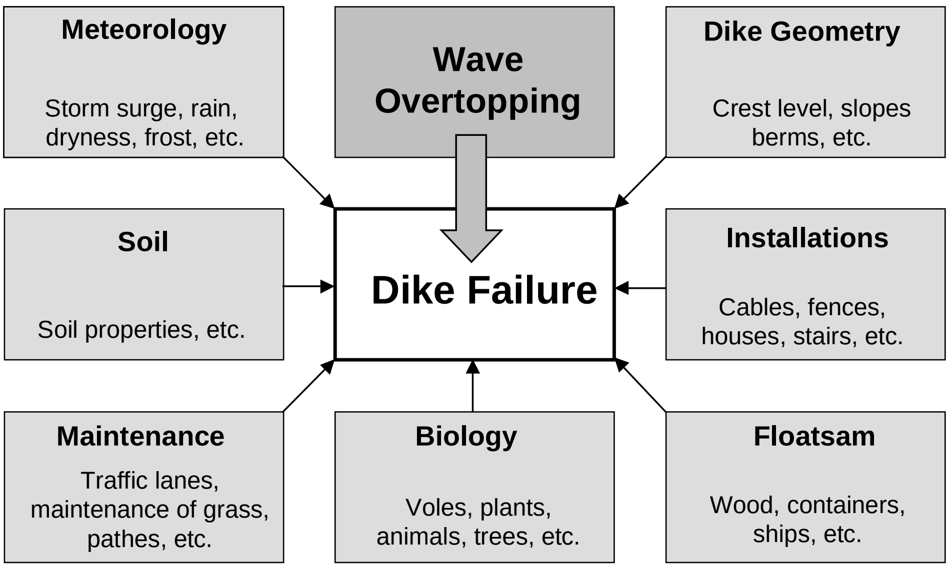


Fig. 3. Causes for Dike Failures

Morphology of Dike Failures

The morphology of dike failures can be classified by the following failure modes:

- turf erosion (soil particles are washed out)
- turf peeling (the turf is peeled from the clay)
- turf set-off (a crack occurs at the upper end of the inner slope)
- en bloc-sliding (the clay of the inner slope slides down the inner slope)
- crown slumping (the crown falls down)
- partial dike break (the crest has collapsed but the toe of the dike is still existent)
- total dike break (the toe of the dike is completely eroded)

These failure modes are determined by the erosion and the infiltration process. Erosion and infiltration occur together, but some failure modes are more influenced by erosion and some failure modes are more influenced by infiltration.

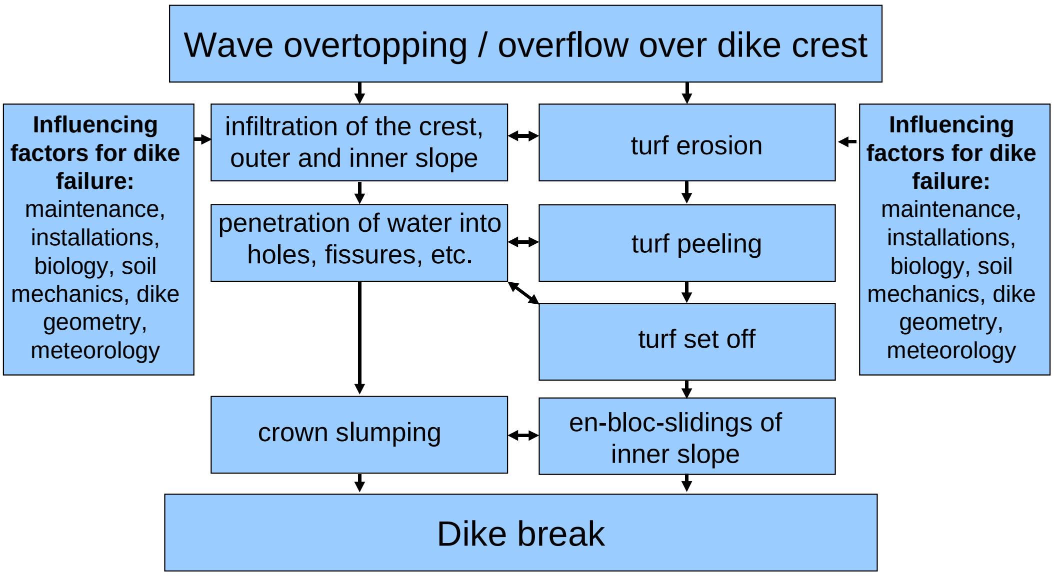


Fig. 4. Dike Failure Modes

Conclusions from Dike Failures

The failure modes are influenced by the overtopping process. Overtopping water is infiltrated into the soil of a dike and the overtopping water is eroding the dike surface of the inner slope. A description of the erosion and the infiltration process is not available in literature and has to be determined by research. A method to predict the initiation of a dike failure and the morphological process of a dike failure until dike breaching has to be developed.

MODEL SET-UP AND TEST PROGRAM

The large scale model tests were used (i) to validate a theoretical model for the description of the overtopping flow process (Schüttrumpf et al., 2002) and (ii) to get model data on erosion and infiltration. All model tests were performed in the Large Wave Flume of the Coastal Research Centre (FZK) in Hanover for a 1:6 seaward slope and a 1:3 landward slope (Fig. 5). The crest was 2m wide and 6m above flume bottom.

The incoming wave field was measured by resistance type wave gauges, wave run-up velocities and wave overtopping velocities by micro-propellers, layer thicknesses in wave run-up and wave overtopping by digital wave gauges, pressures on the dike surface by very sensitive pressure cells and the overtopping volume by a discharge meter and by an overtopping tank installed on four weighing cells. A detailed description of the model set-up is given by Oumeraci et al. (2001). Soil mechanic properties were measured with TDR-probes (water content) and tensiometers (suction tension) on the dike crest and the inner slope at the same positions where the hydraulic parameters are measured. Tensiometers and TDR-probes were placed in 5cm, 10cm, 15cm, 25cm and 35cm depth to investigate the infiltration process. In addition a laser system was installed above the inner slope to measure the deformation of the inner slope and to determine the erosion process.

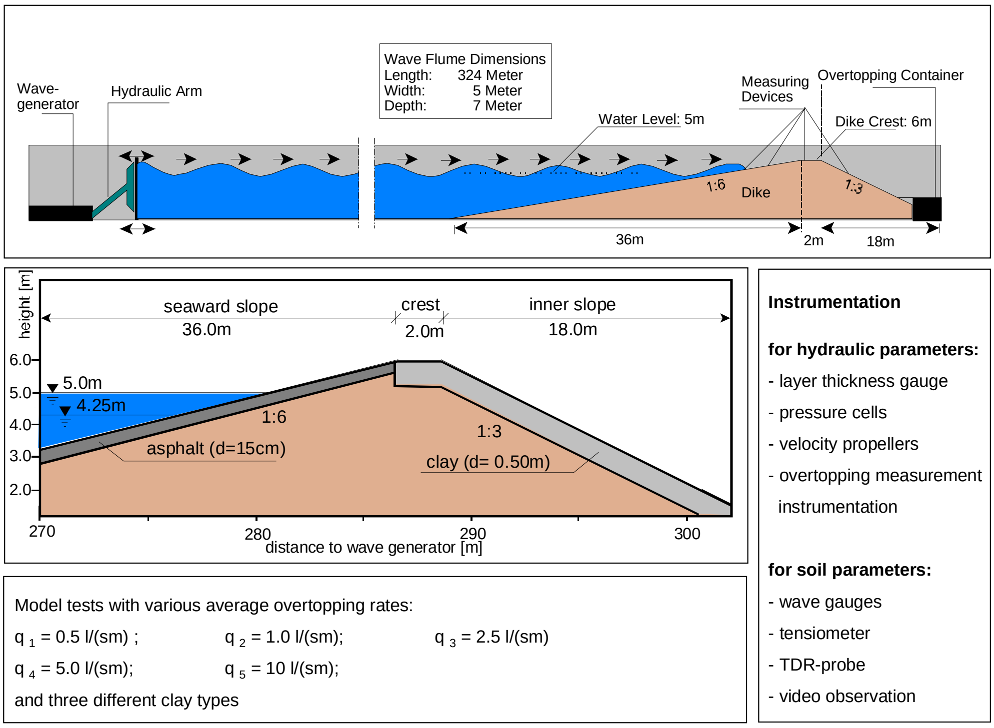
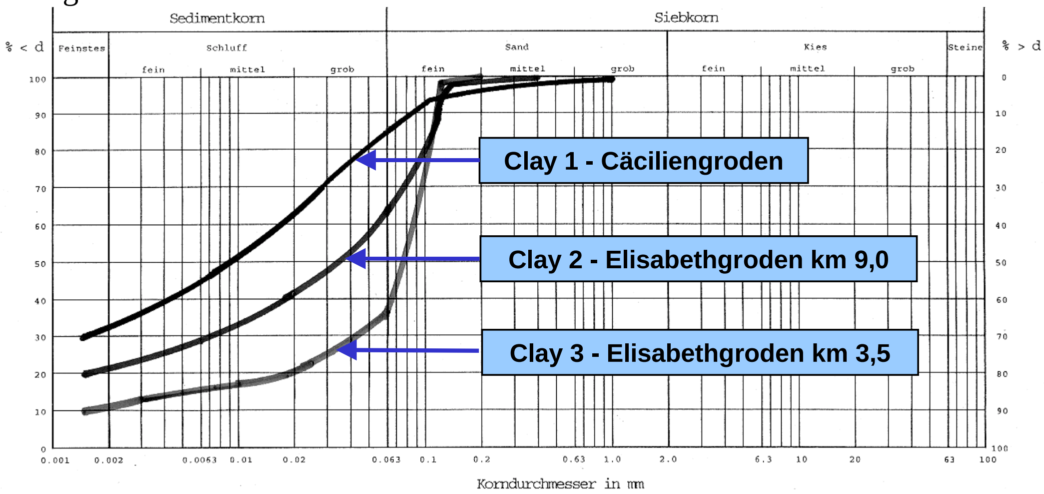


Fig. 5. Model Set-up and Test Program for Large Scale Model Tests

The clays for the experiments were taken from site at three different locations along the German North sea coast. The clay was built in the flume with a digger, distributed by hand and compressed by a vibration roller (Fig. 6).

Fig. 6. Built in of Soil (left) and Compression of Soil in the Large Wave Flume (right)

Three different clays were put in the flume with different grain size distributions. A very thick clay was used for a first test phase (Fig. 7). This clay represents a very resistant clay with a low permeability. In a second test phase, model tests were carried out with a clay which is still acceptable for German dikes and a higher permeability as the first clay (Fig. 7). In a third test phase, model tests were carried out by using a clay with a high percentage of sand.



	Clay 1	Clay 2	Clay 3
Clay	**35%**	**20%**	**10%**
Silt	**53%**	**45%**	**30%**
Sand	**12%**	**35%**	**60%**

Fig. 7. Grain Size Distribution for Model Tests in the Large Wave Flume

All model tests were performed without grass. This situation was assumed to be the situation of a new dike just after construction. The use of grass was discussed in an early phase of the project but it was concluded, that it is (i) very difficult to insert soil with grass in the flume and variations of the soil parameters are practically not possible, (ii) it is not possible to wait until a good grass has grown in the flume and (iii) different types of grass exist which increases the range of possible variations for the wave flume experiments. On the other hand, the use of a fresh soil means that no cracks due to frost or dryness exist and that the aging process of a clay can not be considered. Therefore, additional laboratory investigations are required to study (i) the effect of grass on infiltration and erosion and (ii) the effect of cracks on the infiltration process (the permeability increases significantly in the presence of cracks).

Within this test period theoretical and natural wave spectra with various average overtopping rates are generated. The tests started with small average overtopping rates (q = 0.5 l/(sm)) and the overtopping rate was increased in steps (q≈1 *l*/(sm); 2.5 *l*/(sm); 5 *l*/(sm); 10 *l*/(sm)) until the clay of the dike was damaged completely. For the detailed test program see Richwien and Weissmann (2001). Fig. 8 shows the dike with clay on the crest and the inner slope during the model tests. The first picture (a) shows the situation before starting tests, the second picture (b) shows the erosion on the inner slope after several overtopping events and (c) after several model tests with increasing overtopping rates and (d) shows the erosion at the end of the tests.

Fig. 8. Erosion Process during Model Test (Soil 1, q = 10*l*/(sm))

KEY RESULTS

(a) Initiation of Erosion

It was observed during the model tests, that the erosion process starts with the wash out of small soil particles. The surface of the inner slope which was smooth at the beginning of the model tests became rough with small elevations and holes. These small disturbances in the surface are the starting points for more extensive erosion phenomena like erosion gullies and deep holes. The erosion process continues with the occurrence of erosion gullies. The time when erosion gullies appeared in the experiments was defined as the initiation time for erosion because this moment can be better defined than the moment when first small soil particles are washed out of the soil. A significant initiation of the erosion process (erosion gully) occurs very early for the three investigated clays.

Fig. 9. Inner Slope before Model Testing (left) and
Initiation of Erosion 2 Hours after Model Start (right) (Soil 1, q = 1.0 *l*/(sm))

The initiation of erosion for the first soil occurs for an average overtopping rate of 1.0 *l*/(sm) about 2 hours after start, for the second soil about 1 hour after start and for the third clay about 10 min after start of the experiment with an average overtopping rate of 0.5 *l*/(sm). The resistance of the different soils to wave overtopping is obvious.

The tests in the wave flume have shown, that the erosion process is relevant for the dike faliure, if the turf is damaged or undeveloped. For normal sea dikes with a fully developed turf the infiltration associated with the soil weakening is the main reason for inner slope faliure.

(b) Initiation of Infiltration

Infiltration into the dike happens due to the permeability of the clay. This can be confirmed by the measurements of the TDR-probes and the tensiometers. Fig. 10 shows the infiltration process started at TDR- probe 1 about 3000 s after beginning the experiment and reaches TDR-probe 5 about 11000 s later. This results in an infiltration velocity of about $1.8 \cdot 10^{-5}$ m/s.

Water infiltrates from each overtopping wave, but the signal is smoothened due to the low infiltration velocity, so it is not possible to recognize any individual overtopping event (cp. Fig. 10).

The water content variation over the soil depth is given in Fig. 11 for the dike crest and the top of the landward slope. Overtopping water infiltrates much faster in the dike crest than in the landward slope. This can be explained by higher thicknesses of the water layer on the dike crest (Schüttrumpf et al., 2002) and water which remains on the dike crest in the interval of two different overtopping events. On the landward slope the overtopping water is accelerated and the layer thickness decreases. Therefore, the infiltration process is much slower than on the dike crest. Fig. 11(b) shows also that the infiltration during the test wets only a depth of 15 cm and does not change the water content over the total depth like at the dike crest.

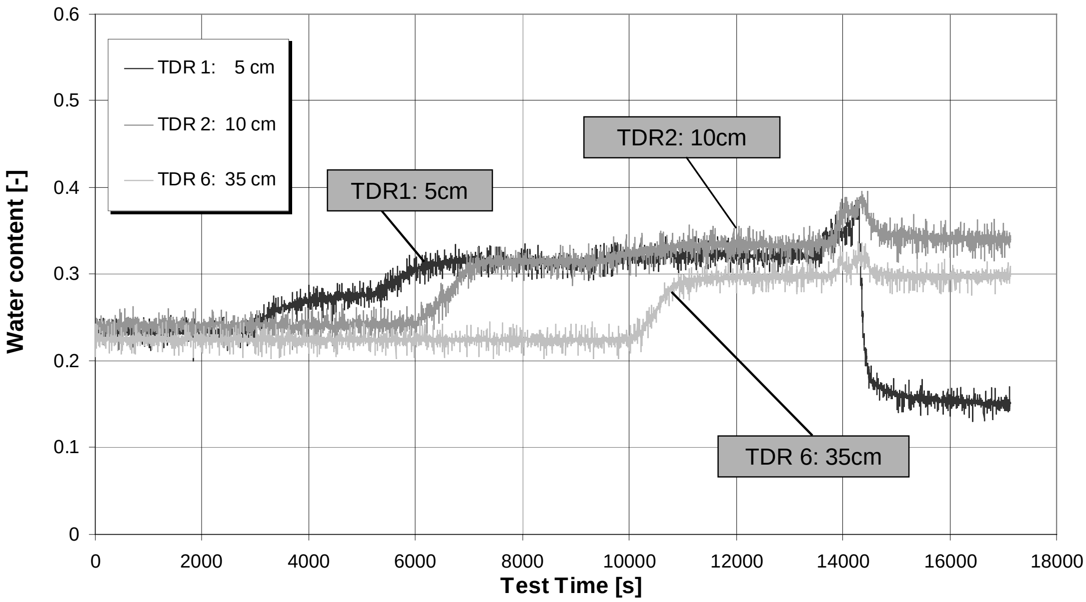


Fig. 10. Water content within the dike crest (soil 3); q = 0,5 l/(sm)

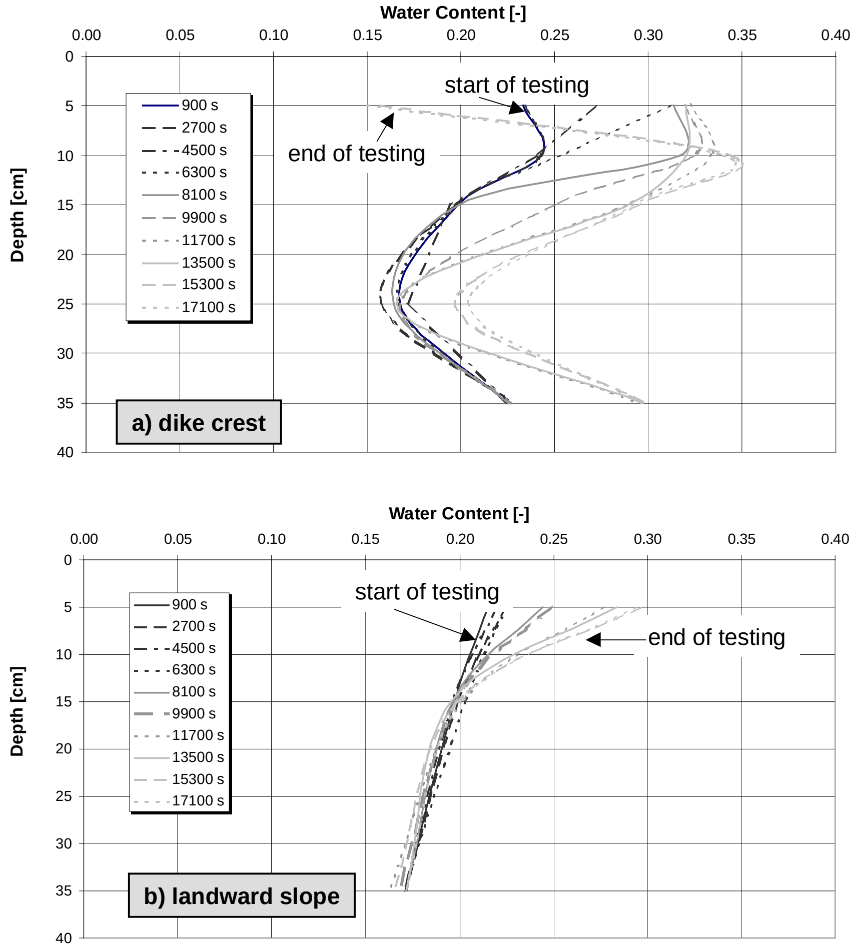


Fig. 11. Water content distribution over clay depth

(c) Failure Process

The failure process starts in case of no turf by the creation of small erosion gullies. During continuous wave overtopping the size of the gullies increases, until deep holes have been developed. In Fig. 8 (a) to (d) four moments of the failure process are shown (Clay 1). It can be seen that erosion gullies and holes have a bigger size near the dike crest than at the inner slope. Fig. 8(a) shows the slope at the beginning of the experiment. In Fig. 8(b) the first erosion gullies have appeared, especially at the left side of the slope. In Fig. 8(c) first holes can be seen at the upper end of the inner slope and in Fig. 8(d) the hole at the upper end of the inner slope has increased and the experiment was terminated shortly after.

For the analysis of the morphological processes, it is necessary to distinguish morphological changes due to wave overtopping and morphological processes in the neighborhood of installations and the flume walls.

The failure process for clay 3 is shown in Fig. 12.The first picture (a) shows the situation before starting tests, the second picture (b) shows the erosion on the inner slope after a testing time of 30 minutes with an average overtopping rate of q= 2.0*l*/(sm) and (c) after the model test with q= 2.0*l*/(sm) (30 miuntes) and 16 minutes with an average overtopping rate of q= 5.0*l*/(sm). In picture (d) a zoom of the situation at the dike crest is presented.

Fig. 12. Erosion Process during Model Test (Clay from Elisabethgroden km 3,5)

CONCLUSIONS

Dikes are designed for wave run-up or wave overtopping and geotechnical stability. It is not possible at the moment to include wave overtopping in geotechnical design. Therefore, investigations concerning the interaction of wave overtopping and soil properties were required to consider wave overtopping in geotechnical design.

The main failure reasons were summarized based on an extensive failures analysis. It can be stated, that dike failures due to wave overtopping often occur in presence of other critical circumstances. The main failure modes were reviewed and summarized. It can be shown, that infiltration and erosion are the dominant phenomena for the failure process.

Large scale experiments were carried out to investigate erosion and infiltration for different soils. It can be concluded from the experiments, that without a grass layer:

- the initiation of a failure starts with the generation of an erosion gully
- erosion is more relevant for the failure initiation than infiltration if the turf or grass are still undeveloped.
- infiltration starts at the dike crest
- individual overtopping volumes can not be identified in the signals of the geotechnical instruments, the single wave is not relevant for the infiltration. More important is the duration of wave overtopping.

More research is required in addition to these large scale experiments which were carried out without grass and without an extensive crack system, both conditions existing in practice. Therefore, the infiltration and erosion process must be described by using the hydrodynamic boundary conditions (wave overtopping) to come up with a prediction formula for the erosion and infiltration process and finally the stability of a seadike.

It can also be concluded from the model tests that erosion starts for low overtopping rates (< 1.0l/(sm)) in the case of a good clay without grass at the surface of the dike. This has be considered for the design of new seadikes and critical average overtopping rates which are available in literature have to be considered very carefully.

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