Evaluation of Full Scale Levee Stability Tests at Booneschans and Corresponding Centrifuge Tests

Évaluation des essais de stabilité de levée grandeur nature à Booneschans et essais par centrifugation correspondants

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ABSTRACT

The IJkdijk project is an international test site for inspection and monitoring techniques for levees. The objectives are two-fold: firstly, to develop and validate new sensor techniques and secondly to perform full-scale failure experiments on levees to understand fundamental behaviour in order to be able to increase the quality of the inspection process and safety assessment of levees. The final goal is to be able to respond timely with appropriate measures. The experiment that will be focused on in this paper is a stability test. In the beginning of 2008, a preliminary full-scale test has been performed to determine the characteristics of the subsoil in the area. The results of this test are needed to optimize the full–scale, heavily monitored levee stability failure test, which is executed in the end of 2008. The full-scale tests also have been simulated on a much smaller scale in centrifuge tests. The paper illustrates the applicability and benefits of modern sensor technology by one of the measured parameters, the horizontal deformations. They seem to indicate trends, already hours before failure occurred and may thus act as an early warning system…

RÉSUMÉ

IJkdijk est un site international d'essai pour l'inspection et les techniques de surveillance des levées. Les objectifs sont doubles : premièrement, développer et valider de nouvelles techniques par capteurs et deuxièmement réaliser des essais grandeur nature d'effondrement de levées pour en comprendre le comportement fondamental afin de pouvoir améliorer la qualité des processus d'inspection et l'évaluation de la sûreté des levées. L'objectif final est de pouvoir répondre à temps avec des mesures appropriées. L'expérience décrite dans ce document est un essai de stabilité. Au début de 2008, un essai préliminaire grandeur nature a été réalisé pour déterminer les caractéristiques du sous-sol dans le secteur. Les résultats de cet essai sont indispensables pour optimiser l'essai grandeur nature, exécuté à la fin de 2008, et dont tous les paramètres seront étroitement contrôlés. Les essais grandeur nature ont également été simulés à plus petite échelle dans des essais par centrifugation. Cet article illustre l'applicabilité et les avantages de l'utilisation de capteurs modernes pour un des paramètres mesurés, la déformation horizontale.

Keywords : levee stability, full scale test, centrifuge, IJkdijk, monitoring

1 BACKGROUND

The Dutch lowlands are protected by many kilometers of dikes. Despite the fact that building dikes started in the late Middle Ages, today designing, constructing and maintaining dikes still involves a lot of empiricism. During high water conditions information on the actual strength of a dike is usually obtained by visual inspection. Questions about the time to failure or the maximum load increase a specific dike location can still withstand are hard to answer. For other technical applications modern sensor technology is used to obtain (sub)soil information. After a dike failure at Wilnis in 2003 (Bezuijen et al., 2005), the question was raised if modern sensor technology could be used to assess extra information on dike conditions. At best the sensor technology could be used as an early warning system. In which, when a monitored parameter would reach a certain value, people are warned and action could be taken.

When using modern sensor technology for an early warning system, it should be known which parameter should be monitored at which interval in time and space and at which location in the cross-section, but also at what point action should be taken and what time frame is available. In order to answer these questions the IJkdijk project was started. The aim of that project is to study the applicability of modern sensor technology as an early warning system for dike failure. This aim will be reached by bringing instrumented embankments to failure at full scale.

Dikes might fail according to different failure mechanisms, each implying different conditions for a possible early warning system. In the early stages of the project three failure mechanisms were chosen to focus on: piping, wave overtopping and full-scale stability. With full-scale stability is meant the occurrence of a sliding plane through both the embankment and the subsoil. The stability mechanism was first tested. The paper describes the stability test including a preliminary field test and centrifuge tests to optimize test design. The first analysis results are discussed. The benefits of modern sensor technology as an early warning system are illustrated by examining one of the many measured parameters; the horizontal deformation measured in the subsoil at the toe of the dike.

2 SUBSOIL

In total 33 Cone Penetration Tests, CPT's and 22 continuous Begemann borings were conducted. An interpretation of the CPTs and borings is used to construct a geotechnical profile along the test field. Figure 1 shows a typical CPT and its interpretation found at the middle cross-section of the test embankment. The depth shown by Figure 1 on the vertical axis is related to the reference datum NAP, which is approximately mean sea level. The subsoil consists of a thin, 0.5 to 1.0 m thick clay layer followed by a 1 to 2 m thick peat layer and a Pleistocene sand layer. The CPTs conducted at the site, some up

Proceedings of the 17th International Conference on Soil Mechanics and Geotechnical Engineering
M. Hamza et al. (Eds.)
© 2009 IOS Press.
doi:10.3233/978-1-60750-031-5-2048

to a depth of 20 metres, did not reach the bottom of the Pleistocene sand layer. The peat has a volume weight of 9.8 to 10.8 kN/m^3 and a water content ranging from 2.0 at the top to 3.0 to 4.8 at the bottom. The volume weight of the top clay is 16.6 kN/m^3 with a water-content of 0.3 to 0.6.

The water table faces a seasonal influence being at ground level during wintertime and at ground level minus 0.5 to 1.0 m during summertime.

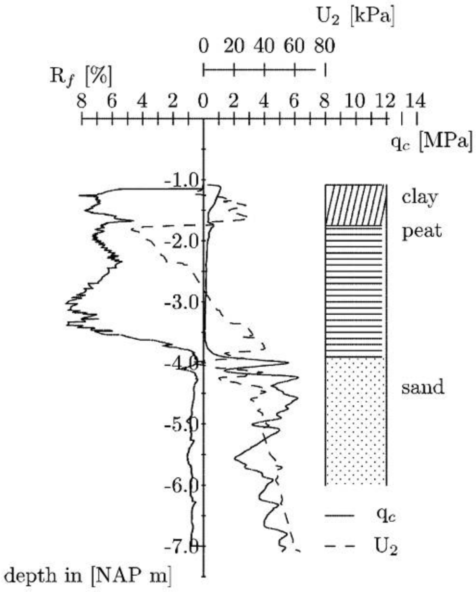


Figure 1. Typical CPT at test embankment

3 TEST SET-UP

The full-scale stability test consisted of constructing an embankment and make it fail in a controlled manner. Figure 2 shows the dimensions of the test embankment. The length of the test dike is 100 m. The test embankment is constructed parallel to an exisiting canal dike. Filling the area between both dikes with water simulated free water at the river or seaside of the test dike, see Figure 8a. The area between both dikes is further referred to as the bathtub. The crest height is 6 m. The slope at the outer side, the sea or river side, is 1:2.5 (V:H). At the inner side the slope is 1:1.5, i.e. the slope that is planned to fail. The available measures for bringing the dike to failure are excavation of a ditch at the toe, filling the sand core with water and application of load on the crest of the dike.

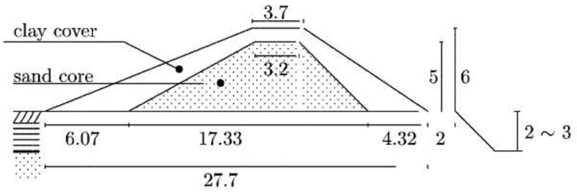


Figure 2. Test set-up, cross section dimensions in [m]

The ditch at the toe of the dike is excavated in two steps. First the top clay layer is removed. Second, when no continuous deformation is found, the ditch is further excavated on to the sand layer.

Filling the sandy core with water requires a heavy and watertight clay cover on the sand core to prevent superficial sliding planes or local leakage and erosion problems. Figure 2 shows the dimensions of the clay cover. The free water, present at the outerside of the dike, increases the safety against sliding of the top clay cover at that outer side of the dike.

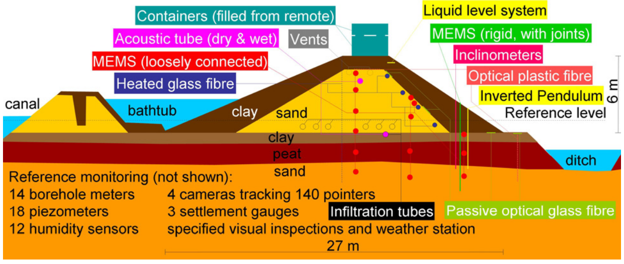
To be able to imply a load on the crest of the dike during the test, two rows of containers were placed on top. By filling these containers with water, a load could be applied on the crest during the test.

The embankment could now be brought to failure by the following steps: 1) filling bathtub at the front of the dike, 2) excavating the top clay layer at the toe of the dike, 3) excavating the ditch at the toe to the sand layer, 4) filling the sand core to 2/3 of its height, 5) filling the containers at the top 6) filling the sand core completely.

4 INSTRUMENTATION

The applied instrumentation is divided into two groups. First is the reference monitoring. This group of instrumentation is used to assist the construction of the embankment, to safeguard the canal dike and to provide reference data to calibrate the new sensor technology with. This group of instruments is also used to guide the experiment. The second type of instrumentation consists of the new sensor technology which usefulness as an early warning system is to be tested. Figure 3 gives an overview of the applied instrumentation.

This figure also indicates the large number of participants testing their newly developed equipment. Not indicated in this figure are thermographic cameras and LIDAR.



Reference monitoring (not shown):

14 borehole meters	4 cameras tracking 140 pointers
18 piezometers	3 settlement gauges
12 humidity sensors	specified visual inspections and weather station

Figure 3. Instrumentation overview

5 PRELIMINARY TEST

Constructing an embankment, without failure during construction and with the intention to bring it to failure shortly after construction, requires an accurate knowledge of subsoil strength. Due to the construction of the embankment excess pore pressures will be present in the subsoil during the test. The excess pore pressures strongly influence the subsoil strength. The exact level of excess pore pressures depends on the permeability of the soil. Among others, den Haan & Kruse (2006) show the difficulty in parameter assessment for peat. Also for the case at hand, problems were encountered, leading to uncertainty in the design of the test embankment. To improve subsoil knowledge a preliminary field test is executed .

In this test two rows of four containers each represented an embankment. By filling the containers with water a load could be activated almost instantaneously. During a period of a week the decrease in excess pore pressure is measured. Next, the containers were emptied and at a distance of one metre from the front container row a ditch is excavated. During excavation the ditch was filled with water. After draining the ditch, the containers were filled again. For the first 25 minutes, no deformation could be observed visually. Then, horizontal displacement of the slope of the ditch was observed, leading to progressive failure of the subsoil 2 to 3 minutes later. Figure 4 shows an impression of the stages of the preliminary test.

Figure 4. a) Overview preliminary test b) Measurement row at the centre of the container row c) Filling of the containers d) Failure

After failure, the containers were removed and the failure plane was examined by excavating an observation pit. The active part of the sliding plane was found to be very steep, followed by a horizontal part through the peat layer, leading to the ditch bottom. It should be noted that for the location of the preliminary test a 2.5 m thick organic clay layer was present on top of the peat layer.

The instrumentation consisted of eight pore pressure transducers placed in the peat and clay layer, two open stand pipes for measuring the hydraulic head in the sand layer, a settlement tube placed underneath the container row, and an inclinometer to measure the horizontal deformations in the subsoil. Figure 5 briefly shows an impression of some of the measurements. The top part of the figure shows the filling of the containers. The lower part shows the horizontal subsoil deformation at a depth of NAP –2.5 m, approximately 1.5 m below ground level, at the front of the first container row and close to the ditch. The figure shows that horizontal deformations were activated directly at the start of filling the containers. This was long before deformation could be observed visually at the surface. The observation that horizontal deformations can be measured before failure is visible is also described in Crabb & Atkinson (1991)

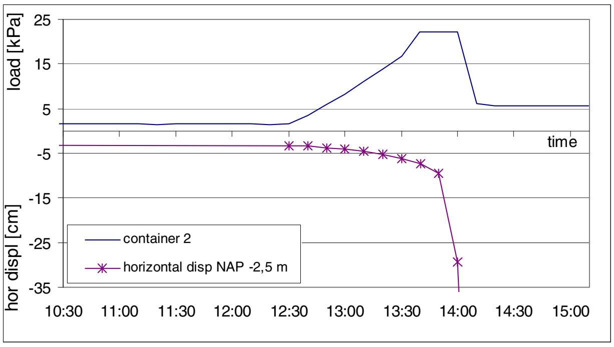


Figure 5. Horizontal deformation of the subsoil at ground level –1.5 m during filling of the containers

6 CENTRIFUGE TESTS

To get more insight on the observed failure mechanism of the preliminary field test, also centrifuge tests were conducted. The test represented the failure of the subsoil underneath the containers during filling. The model is built with a scale of 1:50. The test set-up included the following steps; after reaching the proper g-level a consolidation phase was applied. When the excess pore pressures had disappeared a model in the shape of the ditch was lifted, representing the excavation of the ditch. Next the containers were filled and the water table in the ditch was lowered. To represent the proper sub soil stress conditions the initial water table was placed above the ground level. When emptying the ditch, the water table is also lowered.

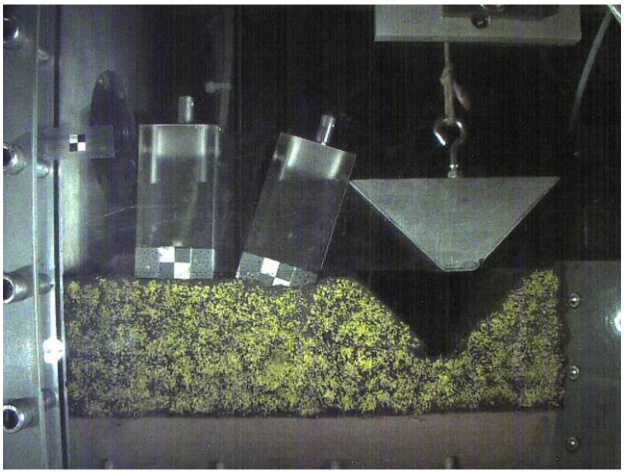


Figure 6. Centrifuge test representing the preliminary test

Figure 6 shows the failure plane observed in the centrifuge tests. Horizontal sliding dominates the failure mechanism. Figure 7 shows the horizontal deformation found in the centrifuge test at three different levels below ground level at the front of the containers. The horizontal displacements are found after creation of vector plots from images like the one shown by Figure 6. The vector plots and the displacement graphs are made using particle image velocimetry (PIV) for use in geotechnical testing(White, 2003). The PIV-analyses was carried out with the PIV software tool developed by White (2002). In comparing centrifuge and the full scale tests, a depth of -18mm in the centrifuge test corresponds to -0.9 m in the full scale test, likewise -28 mm corresponds to -1.4 m and -38 mm to -1.9 m. In the centrifuge test the slip plane lays between -28mm and -38mm. Figure 7 shows that directly when the filling of the containers start, *t* =0, a continuous horizontal deformation starts.

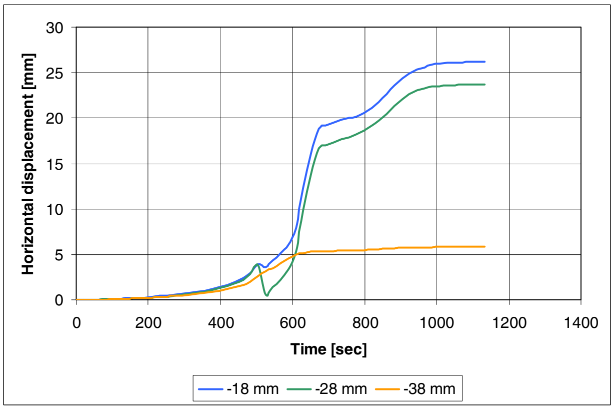


Figure 7. Horizontal deformation at 3 different ground levels in centrifuge test

7 FULL SCALE TEST

The construction phase of the test embankment started on August 13th 2008 and was finished on September 19th 2008. The test started on September 25th by filling the bathtub in front of the dike, see Figure 8a. Later that day the top clay layer was excavated, see Figure 8b, at the toe of the dike. On September 26th the ditch was fully excavated, on to the top of the sand layer, see Figure 8c. On September 27th the sand core was filled with water. The filling started at 12:07h, at 16:00h deformation could be observed visually, failure was found at 16:02h, see Figure 8d.

Failure was reached during filling of the sand core; the containers on top of the dike were not filled. The observed failure plane had a width of 40 m. Equivalent to the preliminary test, horizontal deformation dominated the occurred sliding. After failure was reached an observation pit was excavated to examine the sliding plane. The active part of the sliding plane could not be recovered. Probably the active part is present under the centre of the embankment that could not be reached by the excavation. A long horizontal failure plane was found on the transition of the peat layer and the sand layer.

Figure 8. a) River side of the dike, b) Inner side of the dike during excavation of the ditch, c) Inner side of the dike after excavation of the ditch, d) Failure

Figure 9 shows an impression of the measurements. The horizontal deformation was measured at 1/3 of the inner slope. The initial horizontal deformation, approximately 20 mm, was found during the construction of the dike. Figure 9 shows that, although not visually observed, the horizontal deformations started to develop as soon as the excavation at the toe started. On the morning of September 26th the deformations seemed to slow down until further excavation started around noon. Then, the horizontal deformation accelerated. The next day, the horizontal deformation further accelerated when filling of the sand core with water started at noon, until failure occurred at 16:02h. The measurements show that continuous and consequent horizontal deformation occurs in the subsoil long before it can be observed visually at the surface.

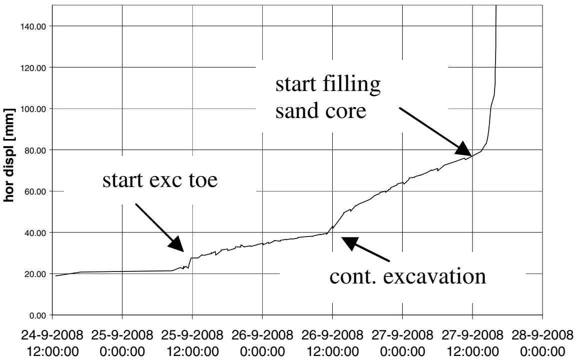


Figure 9. Horizontal displacement at 2 m below ground level

8 SUMMARY AND CONCLUSIONS

The paper discusses the construction and execution of a full-scale field test including a preliminary test and centrifuge tests. The aim of the test is to study the applicability of modern sensor technology as an early warning system against dike failure. From the many measured parameters, this paper focuses on the horizontal deformations measured in the subsoil at the toe of the dike. The horizontal deformation measurements illustrate the possibility for modern sensor technology to act as an early warning system. The preliminary test as well as the full-scale test demonstrate that the measured horizontal deformation shows a continuous deformation long before deformations can be observed visually at the surface. Deformations could only be observed a few minutes before failure occurred. The horizontal deformations seem to indicate trends, already hours before failure occurred.

Although the results are preliminary and a more thorough analysis of the complete set measurement data is required, it can be concluded that modern sensor technology can be used to gain extra information on dike behaviour. Measurements can be used to indicate failure in an early stage.

ACKNOWLEDGEMENT

The authors would like to acknowledge the IJkdijk foundation and Staatsbosbeheer for making the field tests possible.

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