Eemdijk full-scale field test programme: ground dike and sheet pile dike failure test (Programme d'essai terrain à taille réelle Eemdijk: essais de déformation et de rupture pour une digue standard en terre et une digue renforcée avec palplanchesitre)

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Eemdijk full-scale field test programme: ground dike and sheet pile dike failure test

Programme d'essai terrain à taille réelle Eemdijk: essais de déformation et de rupture pour une digue standard en terre et une digue renforcée avec palplanchesitre

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ABSTRACT: Dikes in the Netherlands have traditionally been constructed with soil. Climate change and subsidence requires heightening and or reinforcing these existing dikes. Traditional reinforcements demand additional space, which in some cases conflicts with existing buildings. Applying sheet pile walls in dikes allows for strengthening while minimizing the increase in footprint. However, a validated design approach that complies with relevant regulations lacks. To enable the validation of a proposed design approach, a full-scale field test programme (Eemdijkproef) was performed near the town of Eemdijk, The Netherlands. It consisted of a step wise approach: 1) sheet pile pullover tests, 2) ground dike stability test, 3) sheet pile dike stability test. All tests were loaded until failure occurred. The two similar test dikes were constructed at full scale (5m high, 25m wide, 60m long). In one dike an 18m long sheet pile wall was installed. This paper presents the test setup, monitoring, measurements and first findings. The test program provides better insight in the soil-structure interaction of the reinforced dike, on soft soil, under high water and uplift conditions. Ultimately this will lead to a validated design approach for sheet pile walls in dikes.

RÉSUMÉ: Les digues dans les Pays-Bas sont traditionnellement construites en terre. En raison des changements climatiques et des affaissements de terrain, il devient de plus en plus nécessaire de renforcer et de relever le niveau des digues existantes. Les techniques de renforcement traditionnelles exigent davantage d'espace, ce qui dans certains cas peut empiéter sur l'espace occupé par les bâtiments existants. L'utilisation de murs palplanches permet de renforcer la digue tout en minimisant l'empreinte au sol. Néanmoins, il n'existe aujourd'hui pas de méthode de dimensionnement validée selon les normes en vigueur. Afin de développer une méthode de validation conforme aux normes en vigueur, un essai terrain à taille réelle a été réalisé près de la ville d'Eemdijk (Pays Bas). Cet article présente la configuration, le suivi, les mesures réalisées et les premiers résultats des essais. Le programme d'essai fournit des renseignements sur les interactions entre la digue renforcée et le type de sol, notamment en terrain meuble, sous niveau d'eau et de pression élevés. L'objectif final est de développer une méthode validée de dimensionnement de digues avec utilisation de palplanches.

Keywords: Levee, Dike, Sheet pile, Full-scale failure test, Monitoring instrumentation.

1 INTRODUCTION

The scope of the „Eemdijkproef" is discussed in (Breedeveld, 2019). The main research goal of the full-scale test programme is to gain better insight in the actual behavior of a structural reinforced dike such that a reliable and more economical design is possible.

As part of this test program, two parallel 60m long full-scale test (FST) dikes are built of which one is reinforced with a sheet pile wall. The subsoil consisted of 4.5m soft Holocene soils underlain by sand. The core of the two dikes is constructed with sand and vertical clay cut off walls in between, allowing for independent infiltrating and drainage. Additional loading on both dikes was applied by an excavation of the ditch and by means of containers with water. The aim of the FST is to create a realistic load scenario and failure mechanism. The infiltration of the core of the dike simulates a high water flood. The ditch excavation in front of the dike and lowering of water level simulates the near uplift situation due to high water pressures in the aquifer.

The soil-structure interaction, up to sheet pile failure, is investigated by a seperate pullover test (POT), presented in (Lengkeek, 2019a). These results will be used for the interpretation and analyses of the FST. This paper describes the test setup, monitoring instrumentation and first findings. Comparing the reinforced and normal dike leads to an improved insight in the failure behavior of this type of dike reinforcement.

2 SITE, GROUND CONDITIONS AND TEST DESCRIPTION

2.1 The site

Figure 1 shows the FST site with the sheet pile dike at the NE-side and the ground dike at the SW-side. The POT is located at the W-side. Furthermore the soil investigation points are presented with the Deltares Large Diameter Samples (DLDS) at the E-side.

A cross section of the FST dikes with the monitoring instrumentation is presented in figure 3. More details and a topview of the monitoring is presented in (Breedeveld, 2019). Details of the instrumentation on the sheet piles are presented in Figure 4.

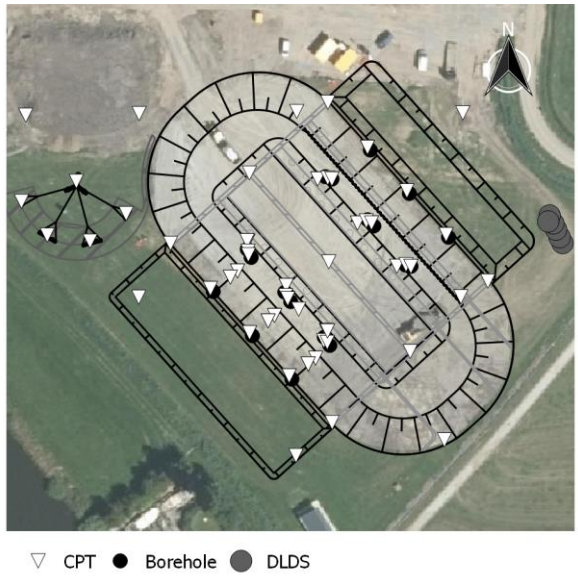

Figure 1 Topview FST site with soil investigation points.

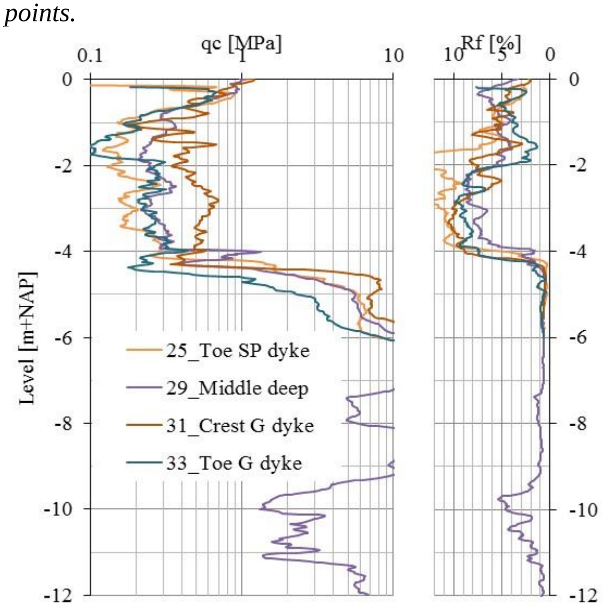

Figure 2 CPT's at toe FST site

2.2 Ground conditions

The subsoil consisted of clay and peat layers underlain by mainly sand layers. The cohesive layers are decisive for the stability. The sand layer is important for the fixity of the sheet pile. A total of 18 Boreholes have been executed at the site. Furthermore 4 large diameter soil samples (DLDS) have been retrieved and tested.

Table 1 shows the identified layers till 12m depth. The site can be classified as homogeneous but there are two main exceptions. At the toe of the ground dike (SW-side) a soft silty clay layer (3a) is present. Furthermore the soil below the crest of the ground dike is preloaded by an old berm. Both exceptions have clearly affected the construction deformations and ground dike stability test.

Table 1. Stratification at FST site (top of layer)

Id	Layer	Ground dike	Sheet pile dike
1	Sand fill (manmade)	5.3	5.5
2	Clay, unsaturated	0.0	0.0
3	Organic clay	-0.8	-0.6
3a	Soft silty clay	-1.5	
4	Peat	-2.0	-1.7
5	Sand	-4.5	-4.2
6	Stiff clay	-9.5	-9.5
7	Deep sand	-11.0	-11.0

Table 2. Classification properties cohesive layers

Id	γ [kN/m³]	γ_sat [kN/m³]	γ_dry [kN/m³]	w [%]	Gs [-]	LoI [%]
3	13.10	13.1	6.0	121	2.23	20
3a	12.6	12.8	5.0	151	2.45	12
4	9.4	10.3	1.4	596	1.50	86

A total of 48 CPT‘s have been perfomed in advance and during construction. Figure 3 presents four CPT‘s that characterize the FST site. All shallow CPT‘s are class 1 according to (EN 1993-5, 2007). CPT25 is located at the sheet pile dike and CPT29 in the middle of the embankment. Both are representative for the entire site. CPT31 is located below the crest of the ground dike and shows a higher cone resistance (qc=0.5 MPa) due to the preloading by an old berm. CPT33 is located at the toe of the ground dike, where a soft silty clay layer 3a can be identified by the low cone resistance (qc=0.1 MPa) at -1.5m NAP.

Table 2 shows the classification parameters: bulk, saturated and dry unit weight. Furthermore natural water content (w), specific gravity (Gs) and loss on ignition (LoI) to determine the organic content. The specific gravity of layer 3a is not measured but derived from the LoI based on (Den Haan, 2006).

An extensive laboratory programme has been perfomed, consiting of Direct Simple Shear tests with constant height (DSS), Anisotropic Consolidated Undrained triaxial compression tests (ACU) and Constant Rate of Strain oedometer tests (CRS). The DSS and ACU tests provided both effective stress and SHANSEP strength parameters to determine the stability. The CRS tests provided the compression and permeability parameters to determine the settlements.

2.3 Sheet piles

One of the two test dikes (NW-side) is reinforced with a sheet pile. It was intended to initially construct a continuous wall of the lightest double Z-profile. After more information was gathered on the strength of the soil and actual yield strength of the sheet piles, the configuration changed otherwise the sheet pile wouldd ultimately not fail. The chosen configuration exists of an staggered wall (18m/9m), consisting of triple U-profiles (GU8N), see figure 2. The properties of the sheet piles are presented in (Lengkeek, 2019a).

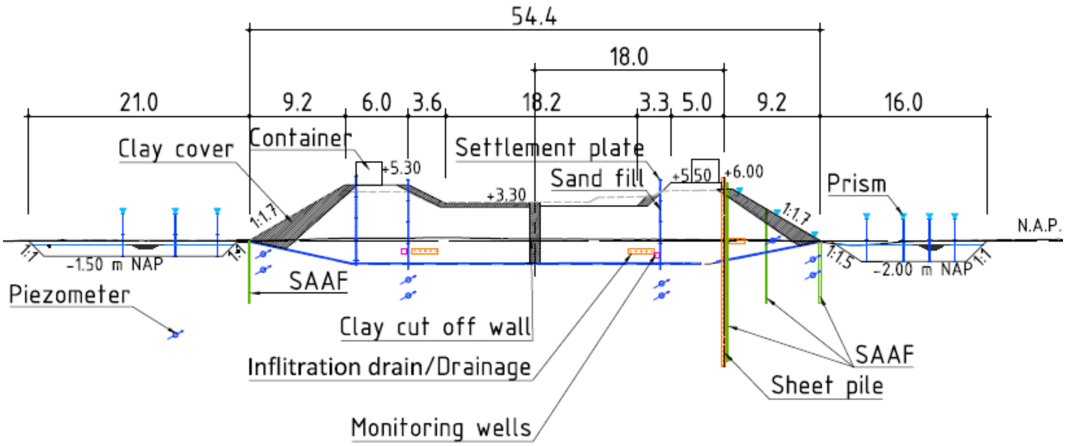

Figure 3 Cross section with on the left side the ground dike and right side sheet pile dike.

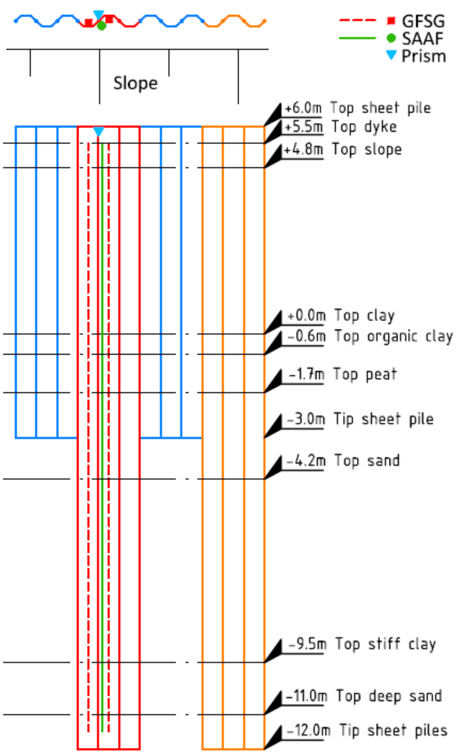

Figure 4 Top and side view of instrumented staggered sheet pile wall.

2.4 Monitoring instrumentation

Figure 3 presents the instrumentation in the cross section of the FST dikes. The construction monitoring comprised: (sub)surface settlement plates, settlement cable, inclinometers (SAAF‘s) in the toe and peizometers. The failure test monitoring comprised: (sub)surface settlement plates, SAAF‘s at the toe, slope and sheet pile, peizometers and monitoring wells, prism‘s on both slopes.

Figure 4 presents the monitoring instrumentation on the sheet piles. The GFSG‘s are placed on both flanges to measure the strains in compression and extension due to the deflection. The SAAF is placed on the web in the centerline to measure the inclination over the full height. A Prim is placed at the top to measure the horizontal deformation.

3 EMBANKMENT CONSTRUCTION MEASUREMENTS

Geotechnical monitoring during the construction was very important. This made it possible to construct the dike within the restricted period (half a year). Furthermore the design was based on a low stability factor (<1.1) because a very stable dike would be very hard to bring to failure, in particular when it is reinforced with a sheet pile.

Figure 5 presents the pore pressures at the toe and below the crest of both dikes (in the middle section). Each stage is clearly visible, in particular below the crest.

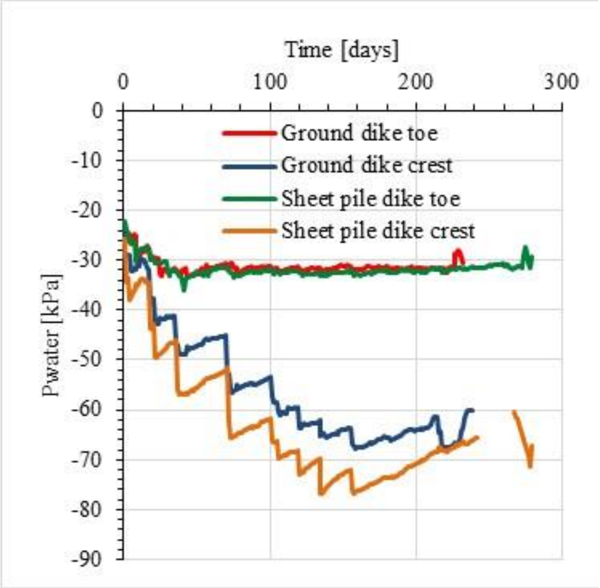

Figure 5 Development of pore pressures during construction.

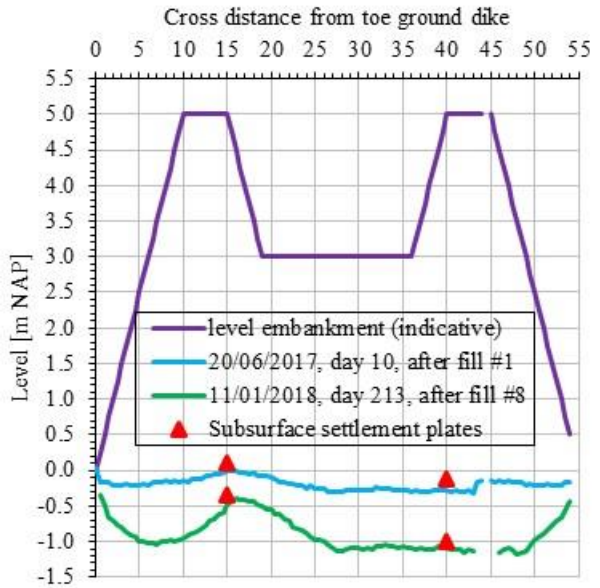

Figure 6 Settlements of the south section after the 1st and 8th fill stage.

Figure 6 presents the settlements along a cross section of the dike, after the 1st and 8th fill stage. The maximum settlement is about 1.1m. The settlement at the old berm location (located under the ground dike crest) is typically half of that due to the preloading. Also the pore pressures at the ground dike crest are lower than at the sheet pile dike cres. The settlement at both the toes is about 0.3m. The horizontal deformations at the toe are about 0.3m at the end of construction. De deformations in the upper 2m where larger at the the toe of the ground dike due to the soft silty clay (3a).

4 TEST PROGRAMME

4.1 Ground dike

The ground dike failure test phases were mainly performed during daytime. The test programme is presented in table 3. During excavation of the ditch the waterlevel is kept constant at -0.2m NAP, during the test at -0.5m NAP and after failure it is slowly lowered to -1.1m NAP. The waterlevel in the sand core of the dike is stepwised increased by infiltration from +0.5m to +2.9m NAP. The liquid-tight containers on top of the dike allowing for additional surcharge were not required in the end.

Table 3 Phases FST ground dike

Test phase	Start time
Excavation 7m ditch -1.5m	24/01/18 8:00
Excavation 13m ditch -1.5m	25/01/18 8:00
Excavation 20m ditch -1.5m	26/01/18 8:00
Water level ditch -0.5m	26/01/18 15:45
Water level fill +1.0m	27/01/18 1:45
Water level fill +2.0m	27/01/18 13:52
Water level fill +2.9m	28/01/18 20:05
Failure	30/01/18 11:15

4.2 Sheet pile reinforced dike

The sheet pile dike failure test was performed 24/7. The test programme is presented in table 3. The phasing follows practically the FST protocol, with slight adjustments during the test and based on the experience during the ground dike test.
The aim of the FST protocol is to create a realistic load scenario and failure mechanism. The infiltration of the fill behind the sheet pile simulates a high water flood. The excavation and

lowering of water level in the ditch simulates the near uplift situation due to high water pressures in the acquifer.

The waterlevel in the ditch is kept constant at 0.5m NAP during excavation and the test. To enhance failure the level is finally lowered to -1.2 m NAP. The waterlevel in the sand core of the dike is stepwised increased by infiltration from +0.5m to +5.0m NAP. The liquid-tight containers on top of the dike were used for additional surcharge.

Table 3 Phases FST sheet pile dike

Test phase	Start time
Excavation 7m ditch -2.0m	12/03/18 7:41
Excavation 15m ditch -2.0m	13/03/18 6:59
Water level fill to +2m	13/03/18 16:45
Water level fill to +3m	14/03/18 17:21
Water level fill/basin to +4.2m	15/03/18 9:18
Water level container 1m	16/03/18 8:24
Water level container 2m	16/03/18 16:00
Water level fill/basin to +4.5m	17/03/18 2:45
Water level fill/basin to +5.0m	17/03/18 10:14
Water level ditch -1.2m	17/03/18 15:25
Failure	17/03/18 16:00

5 DIKE FAILURE TEST RESULTS

5.1 Ground dike

Figure 7 presents the horizontal deformations at the crest (top of the slope) and toe of the dike during the last 3 days of the ground FST. The deformations at the crest are generally 1.5 times smaller than at the toe and became clearly visible by eye one hours before failure.

Figure 8 presents the SAAF measurements at several times. Failure of the slope continues rapidly after 0.1-0.2m horizontal displacement. The slip surface is at -2.0m NAP. Excavations perfomed afterwards confirm a horizontal slip surface in the soft silty clay (3a), and typically circular slip surface in the layers above.

Failure became visually clear due to large cracks developing at the transition of slope and crest, accompanied with horizontal displacements at the toe of the dike. The failure occurred over approximately the middle 30 m of the ground dike, see figure 9a. A large part of the total deformations (several meters) developed in the first hour after the first signs of failure, and steadily increase to its final position, see figure 9b.

Figure 9 Photo's of ground during failure (a) and after failure (b).

5.2 Sheet pile reinforced dike

Figure 10 presents the horizontal deformations at the top of the sheet pile and toe of the dike during the last 3 days of the sheet pile FST. The deformations at the top are generally 1.5 times larger than at the toe and became clearly visuable by eye one day before failure. Failure of the slope started typically at 0.1 to 0.2m displacement.

Figure 11 presents the SAAF measurements at several times. At the early stages the slope provided enough support such that the cantilever wall deflected backwards at the top. Failure of the sheet pile starts after exceeding the maximum bending moment capacity which corresponds with a displacement of typically 0.5m at the top. After failure of the sheet pile, the large deflection finally caused flooding of the FST site (see figure 12b).

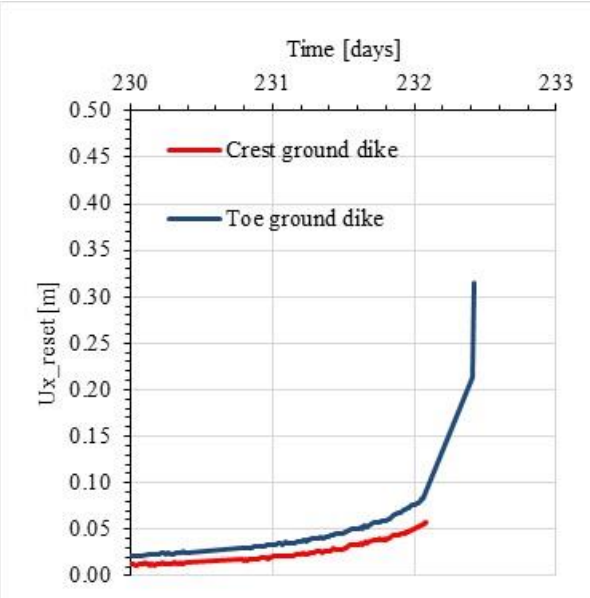

Figure 7 Horizontal displacements of the Prism at the crest and toe of the ground dike.

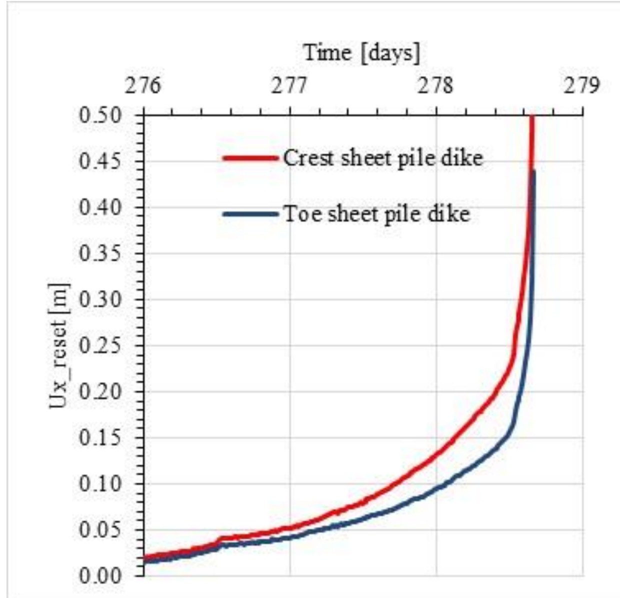

Figure 10 Horizontal displacements of the Prism at the top of the sheet pile and the ttoe of the ground dike.

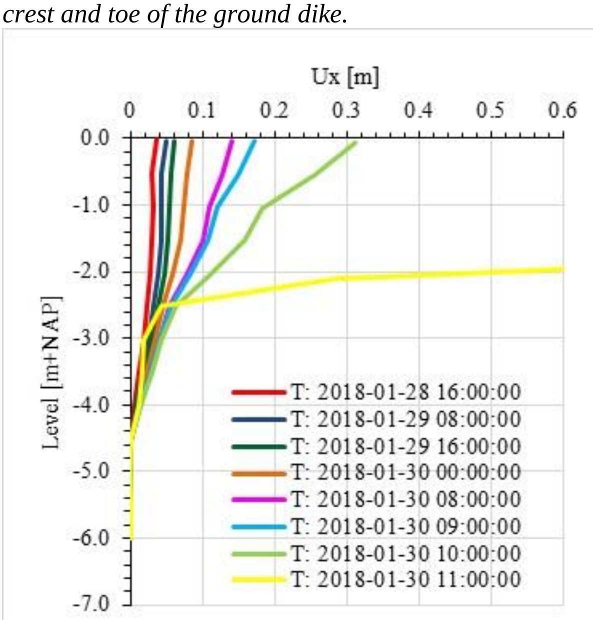

Figure 8 Horizontal displacements over depth of the SAAF at the toe, at multiple times during the ground dike FST.

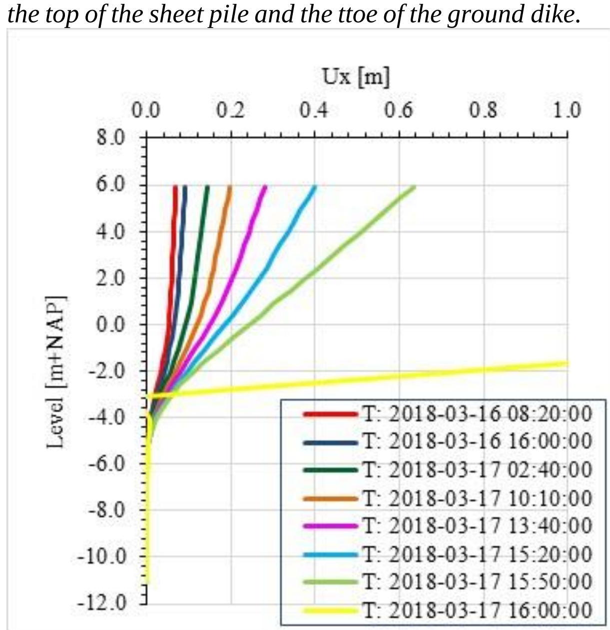

Figure 11 Horizontal displacements over depth of the SAAF at the sheet pile, at multiple times during the sheet pile dike FST.

The SAAF measurements at the toe and slope indicate that the slip surface at the toe of the dike is located at the bottom of the peat layer. Halfway the slope the slip surface is less profound and can beter be described as a failure zone over the thickness of the peat layer. At the sheet pile there is no failure plane because all deformations are imposed by the sheet pile.

The deformations accelerated once the sheet pile failed due to local buckling. The slip surface exited in the bottom of the ditch, approximately 5m from the toe of the dike. The sliding ground mass was pushed upward even above the water level in the ditch, see figure 12a. Deformations stopped once the top of sheet pile was pushed over by 6m and down by 2m.

Figure 12 Photo's of sheet pile dike during failure, just before (a) and during (b) flooding.

6 CONCLUSIONS

Full-scale failure tests have been performed for a ground dike and sheet pile dike to gain better understanding of the failure mechanisme and deformations for both dikes, where the ground dike serves as a reference.

Failure of the slope for both dikes generally started after 0.1 to 0.2m displacement at the toe of the dike.

Deformations of the ground dike are initially very limited. The deformations at the crest are generally 1.5 times smaller than at the toe.

Deformations of the sheet pile ground dike are initially also limited, but at higher waterlevels the deformations at the top of the sheet pile are generally 1.5 times larger than at the toe, providing more (visual) information on the state of the dike compared to the ground dike.

The extensive measurements will provide more information on the soil-structure interaction.

The extensive measurements will be used to validate the geotechnical parameters and use of FEM models.

7 ACKOWLEDGEMENTS

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