Impact of the Eemdijk full-scale test programme (Impact du programme d'essais à grande échelle Eemdijk)

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Impact of the Eemdijk full-scale test programme

Impact du programme d'essais à grande échelle Eemdijk

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ABSTRACT: Levees in the Netherlands have traditionally been constructed from soil. Climate change and land subsidence require heightening and/or reinforcing these existing levees. Traditional reinforcements demand additional space, which in some cases conflicts with existing buildings. Applying sheet pile walls in levees allows for strengthening while minimizing needed footprint. However, a validated design approach that complies with relevant regulations lacked. To enable validation, a full-scale field test programme has been performed near the town of Eemdijk (The Netherlands). This has resulted in better insight in the soil-structure interaction of the structurally reinforced levee, on soft soil, loaded by high water and uplift conditions.

This paper describes the rationale behind the test setup and operation of the test programme in relation to the current design codes and guidelines. First the set of knowledge questions to be resolved is considered. These questions gave direction to the type of failure tests, the required instrumentation and the impact of conclusions.

RÉSUMÉ: Les digues dans les Pays-Bas sont traditionnellement construites en terre. En raison des changements climatiques ainsi qu'aux affaissements de terrain, il devient de plus en plus nécessaire de renforcer et de relever le niveau des digues existantes. Les techniques de renforcement traditionnel exigent davantage d'espace, ce qui est souvent en conflit avec l'espace occupé par les bâtiments existants. L'application de murs de palplanches renforce la digue, et permet aussi de minimiser l'empreinte au sol. Néanmoins, il existe un manque en méthodes de dimensionnement validées, qui se tiennent aux règlements en vigueur. Pour permettre une telle validation, an essai à grande échelle a été réalisé près de la ville d'Eemdijk (Pays Bas). Ceci a permis de mieux définir l'interaction sol-structure de la digue renforcée, sur sol mou, sous des conditions de niveau élevé des eaux souterraines et de soulèvement.

Cet article résume la logique derrière la préparation de l'essai ainsi que l'opération du programme par rapport aux codes et aux directives en vigueur. Le point de départ est une série de questions de recherche à résoudre. Ces questions ont déterminées le type d'essai de défaillance, l'instrumentation requise et les conclusions tirées.

Keywords: sheet pile wall; levee reinforcement; full-scale test; validation; Eemdijkproef;

1 INTRODUCTION

1.1 *Background*

1.1.1 *POV|Macrostabiliteit*

In the national Flood Protection Programme, the Regional Water Authorities and the Ministry for Infrastructure and the Environment jointly take action (e.g. through levee reinforcements) to ensure that the Dutch flood defences satisfy the legal safety requirements. In total, 287 km of levee sections need to be strengthened due to insufficient stability, of which 69.5 km is highly urgent and included in the 2015-2020 program. In order to tackle challenges related to instable levees on soft soil more effectively, the research program „POV|Macrostability“ was established in 2015. In this program Water Authorities, industry and research institutes aim to make stability-improvement techniques qualitatively better, faster to implement and cheaper.

1.1.2 *Problem description*

A frequently applied measure to improve the levee stability under high water loading and uplift conditions, which is expected to increase in relevancy in future, is the installation of a sheet pile wall. With this relatively expensive technique, houses, buildings and other values can be saved.

The high costs for this construction technique are firstly related to the conservative safety philosophy embedded in the current guideline for designing stability-enhancing sheet piles in levees based on FEM calculations. The Dutch Water Act imposes the required reliability standard of the flood defense. From this related partial factors for the assessment of geotechnical resistance of the levee against instability are derived. On the basis of this requirement, the assessment of the resistance against structural failure of the sheet pile wall is largely carried out according to the Dutch Buildings Act. Secondly, the high costs are caused by strict maximum allowed deformation requirements in the design guideline, that often leads to heavy (anchored) sheet pile walls that entirely take over the water-retaining function of the levee.

Unlike a soil structure levee, the structurally reinforced levee is required to apply to strict deformation requirements. In the serviceability limit state both crest settlement and horizontal wall displacement need to be smaller than 0.10 m; in the ultimate limit state the wall deflection is not allowed to exceed 2% of the wall length (with a maximum of 0.5 m). Also, in contrast to what in (EN 1993-5, 2007) is allowed, if class 1 and class 2 profiles are applied, only the elastic (thus not the plastic) capacity of the steel wall may be taken into account according to the design guideline. Finally, the structure is not allowed to obstruct groundwater flow within the levee. This generally leads to a discontinuous wall from panels of several sheet piles, connected with a waling (see Figure 1).

Figure 1: Installation of discontinuous sheet pile wall as reinforcement of Lekdijk Krimpenerwaard

An important motivation for keeping these strict requirements is, that real experience and reliable insight in the actual behavior of a structurally reinforced levee under rarely occuring high water loading and downstream uplift conditions is missing due to the relatively high Dutch safety standards. As a result, validation of the strength and stiffness behavior of this type of levee in the FEM calculation model also is a knowledge gap, which makes it impossible for a sound estimate of the required level of reliability of the FEM analysis. This resulted in unnecassary and costly conservatism in the current design.

1.2 Eemdijk test programme

1.2.1 Objectives

The research within the POV|Macrostability program concerning sheet pile wall reinforcement is based on the hypothesis, that more insight into the actual behavior of the reinforced levee will result in lighter (and therefore more flexible) designs. By incorporating combined behaviour of the sheet pile wall and surrounding soil more accurate into the design rule, the structure will be expected to become substantially cheaper.

This has led to three research objectives: (**i**) the assessment of the actual strength and stiffness behavior of the reinforced levee until failure; (**ii**) the acurateness of the available calculation models can predict this behavior; (**iii**) the availability of a reliable and complete case, so that current and future design approaches can be numerically validated.

1.2.2 Numerical vs. physical experiments

The research has focused on the soil-structure interaction occuring up to and after failure of a structurally reinforced levee on soft soil typical for the Netherlands. Reduction of unnecessary conservatism in the design approach can be reached through both numerical and physical experiments. While a reliable mathematical description of the post-failure behaviour of soil is absent, the objectives require for small-scale or large-scale physical experiments, e.g. as in (Zwanenburg, 2012) and (Zwanenburg, 2015).

The decision, to perform a full-scale failure test on a structurally reinforced artificial levee, has been mainly based on the argument, that the test remains as close as possible to reality.

1.2.3 Failure tests

Based on the hypothesis in Section 1.2.1, a large research program has been programmed around a full-scale failure test on a levee reinforced with an unanchored continuous sheet pile wall (see right-hand side in Figure 2). Also, large-scale pullover tests have been performed, assuming that insight in the failure behavior of the reinforced levee (i.e. system level) could only be gained with sound insight in the post-failure interaction of the sheet pile wall and its surrounding soil (i.e. element level).

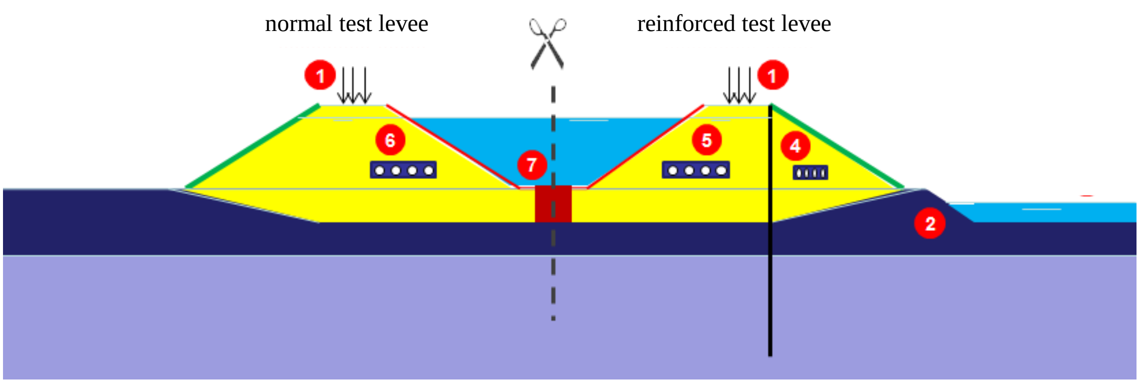

Figure 2: Cross section test levee without (left) and with (right) sheet pile wall with load (1), excavation (2), infiltration/drainage utilies (4, 5 and 6) en clay cut off wall (7)

With regard to *system level*, a full-scale test on a similar levee but without reinforcement (see left-hand side in Figure 2) under comparable subsoil, high water and uplift conditions was carried out. The behavior of this test levee is the reference for the more complex behaviour of the structurally reinforced levee.

The interaction between a structurally failed unanchored sheet pile wall and the surrounding soil, and the residual soil strength after the collapse of the inner slope (that supports the sheet pile wall to an important extent) have been the most important research questions on *element level*. These questions have led to four pullover tests on different panels of multiple sheet piles as well as extensive laboratory research, in which triaxial and DSS tests on the residual strength of large soft soil samples (diameter of 0.40 m) have been executed.

For the detailed test setups and first findings, the reader is referred to the ECSMGE conference papers in the reference list.

1.2.4 Knowledge questions

With the research objectives in Section 1.2.1 and the strict design requirements mentioned in Section 1.1.2 in mind, the following knowledge questions have been formulated:

What are the deformations of the reference levee and reinforced test levee until failure? The monitoring related to this question has focused on the development of deformation over time at the crest, inner slope (including top of sheet pile) and excavation. At the inner slope and over the sheet pile length the development of deformation in depth has also been measured. Before and after the failure of both test levees the cross-section (including residual profile) has been extensively measured.

To what extent does a sheet pile embedded in the soil behave according to (EN 1993-5, 2007) after the creation of a plastic hinge? The monitoring related to this question has focused on the development of deformation over time at ground level (inner slope) and at the head of the sheet pile. In the subsoil and over the sheet pile length the development of deformation in depth has been measured. Moreover, the development of strain over time in the relevant (upper) part of the sheet pile length has been measured.

What influence do the (dis)continuous character and degree of embedment of the sheet pile wall have on the class according to (EN 1993-5, 2007)? The monitoring related to this question has focused on the differences, as a function of time, for the different sheet pile configurations in the deformation on the ground, in the subsoil and over the wall length, and of the strains in the sheet pile.

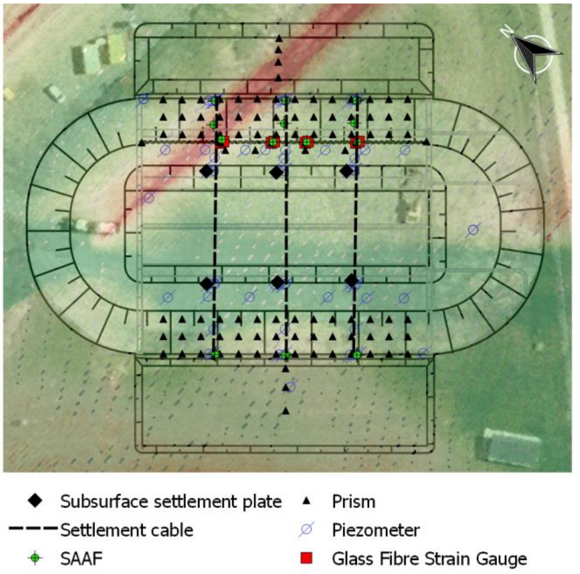

Figure 3: Monitoring campaign during test levee heightening and test performance

2 MONITORING CAMPAIGNE

Both during the (staged) construction of the artificial test levees as well as before, during and after the failure tests, an extensive monitoring campaign aiming at geotechnical and structural aspects has taken place in multiple cross sections (see Figure 3).

2.1 Test levee construction

The primary aim of geotechnical monitoring during test levee heightening has been to raise the test levees as quickly and as safely as possible (i.e. without loss of stability) in eight layers of 0.5 m to 1 m thick (see Figure 4).

The development of resulting settlements during heightening was followed with settlement plates and subsurface settlement plates, while the development of horizontal soil deformations was mapped with inclinometers. The development over time of the shear strength in the cohesive soil layers has been deducted from excess pore pressure development and CPTs.

The Observational Method approach (i.e. the continuous comparison of the measured and predicted settlements and consolidation) gave an improved insight into the actual properties of the subsoil at the test locations.

2.2 Sheet pile pullover tests (POT)

2.2.1 Test description

In four pullover tests (see Figure 5) on different configurations of sheet piles, panels were pulled over in order to investigate the soil-structure interaction after the development of a plastic hinge in the configuration. Two GU8N triplets (both in the strong as in the weak direction), a panel of three double AZ13-700 piles and a panel of three double AZ26 piles have been tested until failure. The pulling over took place by retracting (at a constant speed) a hydraulic jack placed between the configuration and a reaction frame. See (Lengkeek, 2019a) for detailed description.

2.2.2 Monitoring

With regard to the POT monitoring (see Figure 5), the pullover force has been measured with a force gauge between the hydraulic jack and the sheet pile configuration, while the jack displacement has been recorded with an optical sensor. The development of deformation over time during each POT has been monitored with a total station that measured prisms at ground level (in front of the panel) and at two levels on the panel. The development of deformation in depth was monitored with Shape Accel Array Fields (i.e. SAAFs) both in the neutral line of the sheet pile and in the subsoil in front of the sheet pile. To conclude, the development of strain over time over the relevant part of the sheet pile length was measured with glass fiber sensors in both a flange under compresion as in a flange under tension.

After the performance of all four pullover tests, the distorted sheet pile configurations have been excavated just below the level at where buckling had taken place for visual inspection. Thereafter, 3D laser scans have been made of the distorted sheet pile configurations.

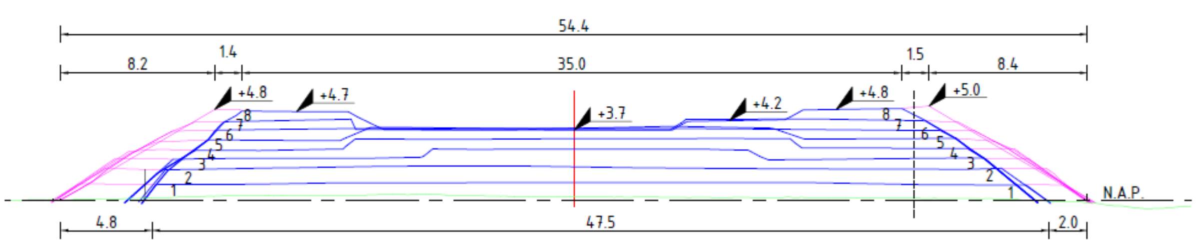

Figure 4: Layered construction of test levees

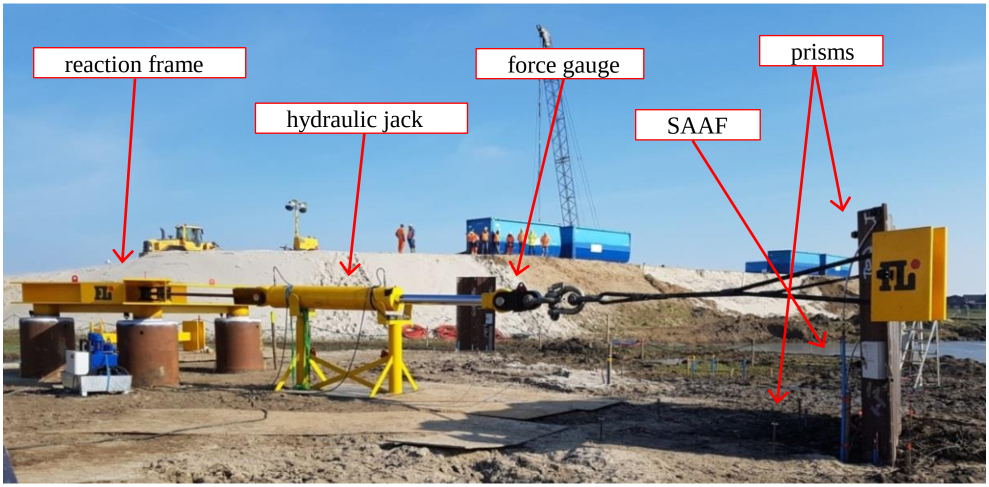

Figure 5: Setup for POT on a sheet pile panel

2.2.3 Analysis test results

The influence of the degree of discontinuity of the panels on the soil-structure interaction was investigated by comparing the results of the (narrow) GU8N triplets with those of the ('continuous') panels of three double AZ piles. Also the influence of (EN 1993-5, 2007) class on the behavior was investigated, by comparing the results of the AZ13-700 (class 3) and AZ26 panel (class 2). Finally, the influence of the load direction on the behavior was also investigated, by comparing test results of both GU8N triplets.

2.3 Full-Scale Test (FST)

2.3.1 Test description

In two separate full-scale tests high water and uplift conditions have been imposed on a 60 m long test levee, until insufficient resistance to instability made the levee fail. With an extensive monitoring campaign, a controlled stepping up of the extreme conditions was established, and the behavior until failure was accurately recorded. A staggered wall built up from alternately long and short GU8N triplets was installed in the structurally reinforced levee.

In both FSTs the application of the high water and uplift conditions has consecutively consisted of saturating (i.e. weakening) the sand core(s), increasing the levee instability by filling the waterbasin (only reinforced levee), raising the crest load and creating uplift conditions by lowering the water table in a 15-20 m wide excavation (see Figure 6). In (Lengkeek, 2019b) a more detailed description is presented.

2.3.2 Monitoring

Figure 7 gives an impression of the monitoring during both FSTs. The development of deformation over time of the inner slope (including sheet pile head) has been followed with a total station that measured dozens of prisms at three levels in the outer contour over the entire length of 60 m.

The development of deformations in depth has been measured in three cross sections (see Figure 3) with a SAAF in the inner toe, halfway the inner slope and in the crest (at the reinforced levee on the slope side of the sheet pile wall). The vertical deformation of the excavation bottom has been monitored by periodically measuring settlement plates placed thereon.

In four sheet piles within the wall, the development of strain in depth over a large part of the sheet pile length has been measured with glass fiber sensors in both a flange under compresion as in a flange under tension.

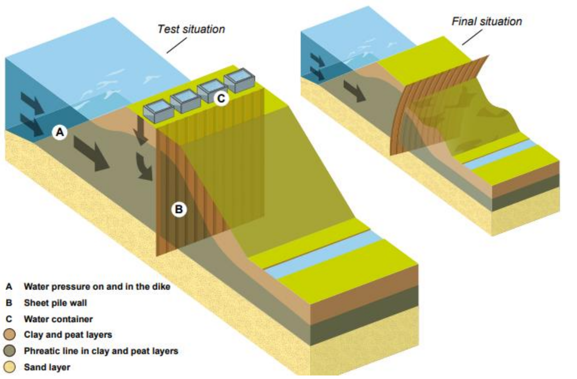

Figure 6: Application of extreme conditions in FST on structurally reinforced levee

During the test on the structurally reinforced levee, a 3D laser scan has been periodically made, and video recordings of the complete failure test run were made of both test levees.

2.3.3 Analysis test results

Comparison of the behavior of both test levees has shown that, with respect to the deformation in the inner toe, they have similar failure behavior (in both cases at 10-20 cm). However, at crest level the behavior has been different: just before failure, crest deformation of the normal levee had been in the order of magnitude of centimeters, whereas the deformation at the reinforced levee (albeit at a higher load) had been in the order of decimeters. The reinforced levee gave more warning signals of failure than the normal levee.

2.3.4 Analysis residual profile

The postdiction of the actual deformations of the failed inner slope at the normal levee required assuming half of the peak strength of the soil. This amount of reduction had been much more than the laboratory test results from triaxial and DSS tests on large clay and peat samples. This difference between the results from the test and the laboratory research has meant that no clear conclusion could be drawn about the residual soil strength.

3 CONCLUSIONS

The conclusions from the research program designed around the full-scale test on a levee reinforced with an unanchored sheet pile wall with respect to the aforementioned knowledge questions are as follows:

3.1 Deformations until failure

The current design guideline for sheet pile wall reinforcement imposes strict requirements on the deformations in both the serviceability and ultimate limit state. However, the (undrained) deformation of the structurally reinforced levee in the test has shown to be strongly related to the stability of the levee or sheet pile wall.

The deformations caused by the high water load are limited for a stable levee, regardless

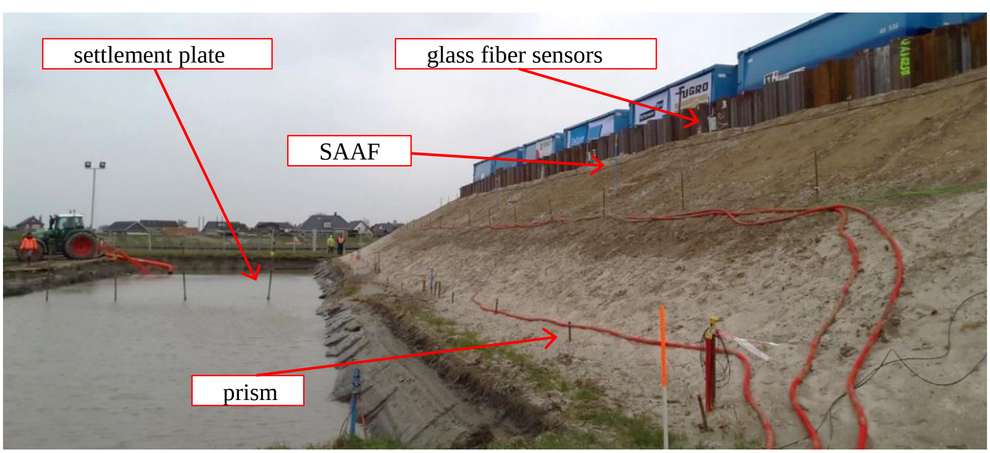

Figure 7: Monitoring campaign FST on (non-)reinforced test levee

whether the levee is structurally reinforced or not. Therefore, it seems sufficient to assess the levee‘s strength and stability in the ultimate limit state only. In that case, deformation requirements are only relevant for the construction phase.

The current design guideline prescribes FEM analyses with drained soil behavior based on characteristic strength parameters. In numerical postdictions of the FSTs (with undrained soil behavior) it has appeared sufficient to take average values for both the strength and stiffness parameters into account to reproduce the actual deformations. On this basis, a model factor on the deformations (as requested in the Eurocode approach) due to high water could be set to 1.

3.2 *Influence of plastic hinge*

The current design guideline only allows, even for class 1 and class 2 profiles according to (EN 1993-5, 2007), to take into account the elastic capacity. However, based on POT results it is recommended to use the Eurocode approach for the structural assessment of the sheet pile wall. On the condition that panels consist of at least three double sheet piles, the plastic capacity can be taken into account for relatively heavy class 2 profiles.

3.3 *Influence of discontinuous character*

The current design guideline considers it desirable that the sheet pile wall does not affect the groundwater regime in the levee. In general, this requirement leads to a discontinuous wall built up of panels connected by a waling. Piles within a panel are on both sides and over the full length connected through it‘s locks; the edge piles of panels have a lock connection on only one side. In order to cover the possible influence of this on the stiffness properties of the edge piles, the current guideline recommends a 10% reduction of the section modulus.

The pullover tests on several sheet pile configurations have shown that no reduction of the section modulus for edge piles is required, provided that the discontinuous walls consists of panels of at least three double piles.

The full-scale test on the reinforced levee has also shown that a structural reinforcement of a levee with a continuous wall offers advantages. Not only because it offers the opportunity to redistribute the loads both in the vertical and longitudinal axis of the levee, but also because it has shown in the that after structural failure it is still contributes to the water retaining capacity of the levee.

4 ACKNOWLEDGEMENTS

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5 REFERENCES

EN 1993-5:2007 Eurocode 3: Design of steel structures – Part 5: Piling

Lengkeek, H.J., Naves, T., Post, M., Breedeveld, J. 2019a. Eemdijk full-scale field test programme: sheet pile pullover tests. *Proceedings*, *ECSMGE 2019 Congress*. Reykjavik.

Lengkeek, H.J., Post, M., Breedeveld, J., Naves, T. 2019b. Eemdijk full-scale field test programme: ground levee and sheet pile levee failure test. *Proceedings*, *ECSMGE 2019 Congress*. Reykjavik.

Zwanenburg, C., Den Haan, E.J., Kruse, G.A.M., Koelewijn, A.R. 2012. Failure of a trial embankment on peat in Booneschans, The Netherlands, *Géotechnique* **62**, No. 6, 479-490.

Zwanenburg, C., Jardine, R.J. 2015. Laboratory, in situ and full-scale load tests to assess flood embankment stability on peat, *Géotechnique* **65**, No. 4, 309-326.