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Eemdijk full-scale field test programme: sheet pile pullover tests

TProgramme d'essai terrain à taille réelle Eemdijk : essais de déformation et de rupture de murs palplanches

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ABSTRACT: Dikes in the Netherlands have traditionally been constructed with soil. Climate change and subsidence requires heightening and or reinforcing of these existing ground 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 full-scale pullover tests (POT) consisted of 4 sheet pile configurations. The length of the sheet piles varies between 13 and 16m and the width of the panel varies between 1.8 and 4.2m. Both Z- and U-profiles have been tested. This paper presents the test setup, monitoring, measurements and first findings. The test program provides better insight in the soil-structure interaction of an embedded sheet pile in soft soil. 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 essai fut réalisé suivant une approche par étapes : 1) essais de déformation et rupture, 2) essais de stabilité de la digue de configuration standard en terre, 3) essais de stabilité de la digue de configuration avec palplanches. Le programme d'essai fournit des renseignements sur les interactions entre la configuration des palplanches et le type de sol, notamment en terrain meuble. L'objectif final est de développer une méthode validée de dimensionnement de digues avec utilisation de palplanches.

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

1 INTRODUCTION

The main research goal of the Eemdijk full-scale field test is to gain better insight in the actual behavior of a sheet pile reinforced dike, such that a reliable and more economical design is possible. The test programme consisted of the construction of two 60m long full-scale test (FST) dikes which are loaded until failure. One dike is a normal ground dike which serves as a reference for the other dike reinforced with a sheet pile wall. Next to the construction and loading of these test dikes sheet pile pullover tests (POT) have been performed to gain more insight in the soil-structure interaction behavior up to failure. The scope of the „Eemdijkproef“ is discussed in detail in (Breedeveld, 2019). The setup and factual results of the FST dikes are discussed in more detail in (Lengkeek, 2019b).

In the POT a pulling force by constant rate of displacement is imposed on the top of a embedded partly free-standing cantilever sheet pile. The total displacement imposed on the sheet pile is well beyond the maximum (peak) capacity. This paper describes the test setup, monitoring instrumentation and first factual findings.

2 SITE, GROUND CONDITIONS AND TEST DESCRIPTION

2.1 The site

The pullover tests are performed near the town of Eemdijk. A more detailed description of the test site is presented in (Breedeveld, 2019).

2.2 Ground conditions

The ground conditions at the test site are homogeneous, consisting of peat and clay layers on top of a sand layer. In Figure 1 a representative CPT is presented and Table 1 presents the stratification. The “Eemdijkproef” comprised an extensive field and laboratory testing programme. A more detailed description of the geotechnical conditions is presented in (Lengkeek, 2019b). During the testing period temperatures where quite low, except for the first test.

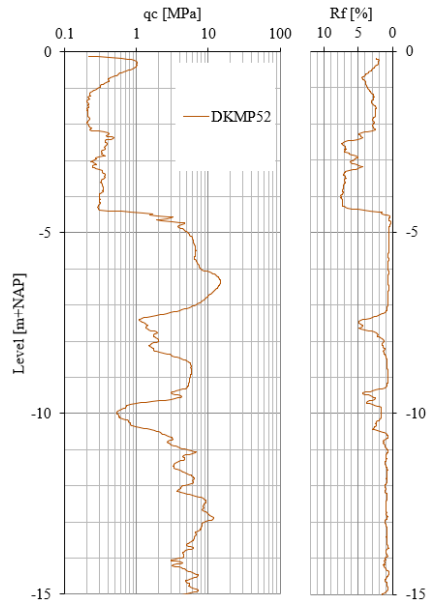

Figure 1. Representative CPT at POT site

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

Id	Layer	level [m NAP]
2	Clay, unsaturated	0.0
3	Organic clay	-1.0
4	Peat	-2.1
5	Sand	-4.5
6	Stiff clay	-7.2
5	Sand	-8.0
6	Stiff clay	-9.2
7	Deep sand	-10.5

2.3 Sheet pile data

Four sheet pile configurations are tested in the POT (see figure 2):

- GU8N triple is a class 3 profile according to the (EN 1993-5, 2007) and the same type as used in the FST sheet pile dike. To assess the influence of the loading direction, this profile is also tested in the reversed direction (GU8N-rev).
- AZ26 profile is tested to validate the plastic bending capacity since this profile is a class 2

profile according to the (EN 1993-5, 2007) and therefore is expected to reach the full plastic bending capacity with additional plastic rotation capacity.

- AZ13-700 is a class 3 profile according to the (EN 1993-5, 2007) and is tested for comparison with the AZ26 profile. It is expected to reach the expected elastic bending capacity (plastic resistance in term of Eurocode) but not the full plastic bending capacity.

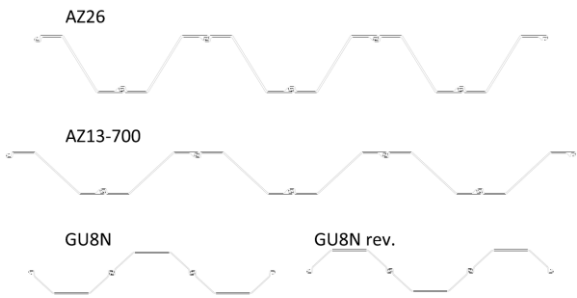

Figure 2. Sheet pile profiles

Table 2. Sheet pile properties

Type	σ_y [N/mm^2]	Wel [cm^3/m]	Wpl [cm^3/m]	I [cm^4/m]
AZ26	327	2603	3062	55579
AZ13-700	406	1306	1542	20552
GU8N triple	380	604	910	11128
GU8N continuous	388	757	939	11807

In table 2 an overview is given of the structural properties of all the sheet piles based on thickness measurement and tensile tests. In case of the GU8N triple, the centerline is not exactly in the middle of the profile and therefore this profile has a reduced section modules and moment of inertia compared to a continuous wall. The values of the full plastic section modules are theoretical values as local buckling is expected to reduce the capacity for the class 3 profiles. Ultimately the POT measurements will be used to determine the maximum capacity.

2.4 Sheet pile pullover tests

The test setup is presented in figure 3. Four sheet pile configurations are placed in a circular formation around a reaction frame. This reaction frame consists of 3 tubular piles interconnected with a steel Y-frame. To prevent any soil interaction between the sheet piles and the reaction frame the sheet piles are installed at a 15m distance of the tubular piles.

Between the reaction frame and the sheet piles a hydraulic jack is placed 2m above surface level, see Figure 4. This jack can generate a pull-force of 1200kN and has a stroke of 2m. This jack is placed on a sliding table to support the jack and prevent the self-weight of the system to influence the behavior of the sheet pile. The jack is connected to a steel cable to both sides of a waling on the sheet pile. This connection is such that the pull-force is evenly distributed over both sides of the waling and the pull force remains centric on the waling even for large rotations of the sheet pile wall.

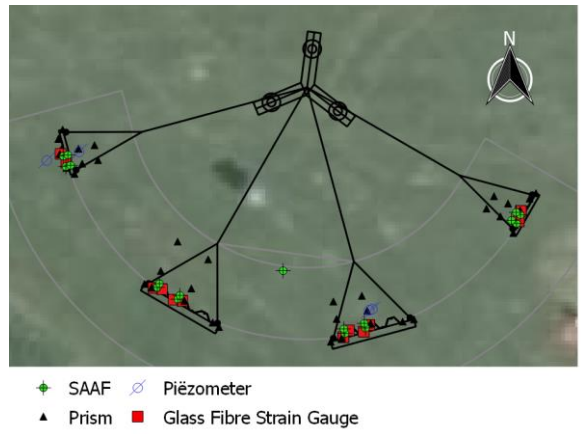

Figure 3. Top view POT site with monitoring instrumentation

2.5 Monitoring instrumentation

To monitor the horizontal displacements of the sheet pile, prisms are placed at three levels on the sheet pile and are monitored with total stations. Two SAAF's (Shape Accel Array Field) are

installed on the sheet pile wall and two SAAF's in the ground at 0.3m in front of the wall centerline to monitor the deflection and horizontal displacements over depth. The total pulling force applied by the hydraulic jack is measured by a force gauge and the stroke of the hydraulic jack is measured by an optical sensor. On the sheet pile wall glass fiber strain gauges (GFSG) are installed.

Figure 4. Photo of AZ13-700 during the test

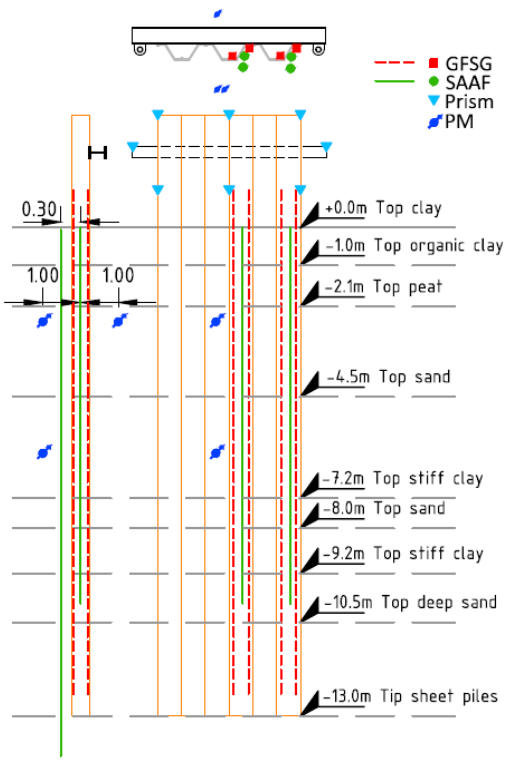

Figure 5. Top, front and side view of instrumented AZ26 sheet pile panel.

3 SHEET PILE PULLOVER TESTS RESULTS

3.1 GU8N triple-U

The GU8N triple-U is the same profile as applied in the staggered wall of the FST sheet pile dike (Lengkeek, 2019b). In this setup two flanges are facing to the reaction frame and will be loaded in compression while one flange will be loaded in tension.

The maximum pulling force reached during this test is 180kN. The fixation level where rotation starts is about -2.0m NAP. Upon reaching 30cm of displacement the SAAF's on the sheet pile wall are removed to prevent any damage due to local buckling of the sheet pile. For this the pull-force is temporary lowered to 100kN. A similar procedure is also followed for the other tests. The obtained force-displacement diagram for the GU8N is shown in figure 6. In figure 7 the horizontal displacements measured by the SAAF and prisms are plotted just before removal of the SAAF. In this figure the SAAF's in front of the wall are also shown with an offset of 1m, in reality they are placed at 0.3m distance of the centerline of the sheet pile wall.

3.2 GU8N-rev triple-U

The GU8N-rev triple-U is the same profile as the GU8N triple-U but loaded in the opposite direction. This means that one flange is in compression and two flanges are in tension.

Figure 8 shows the maximum pull-force is almost 180kN, which is approximately the same as the GU8N triple-U profile. The reduction in pull-force after reaching the peak is however significantly larger compared with the GU8N triple-U profile. Figure 9 shows the deformations of the GU8N-rev triple-U profile and the layout is similar to figure 7

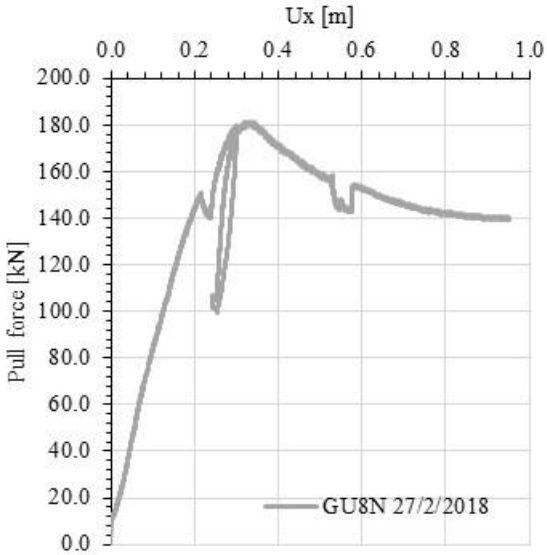

Figure 6. Force-displacement diagram GU8N.

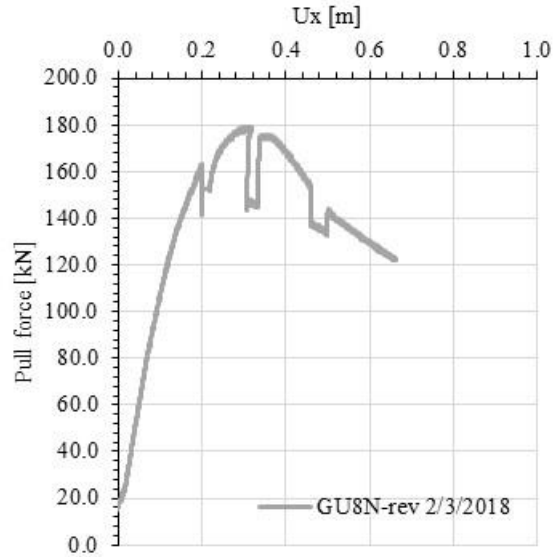

Figure 8. Force-displacement diagram GU8N-rev

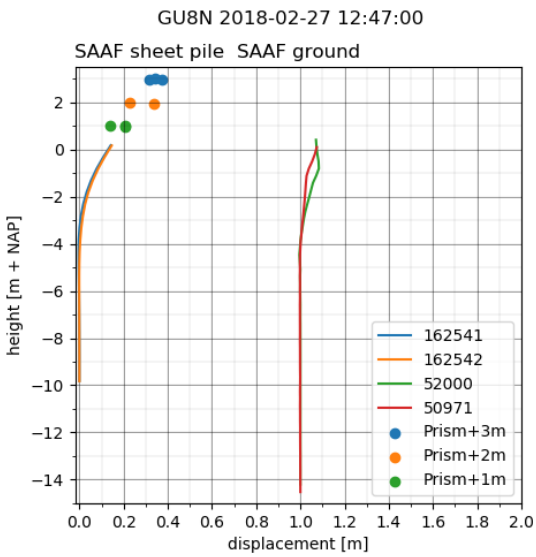

Figure 7. Horizontal displacements over depth of the SAAF and prisms at the GU8N sheet pile.

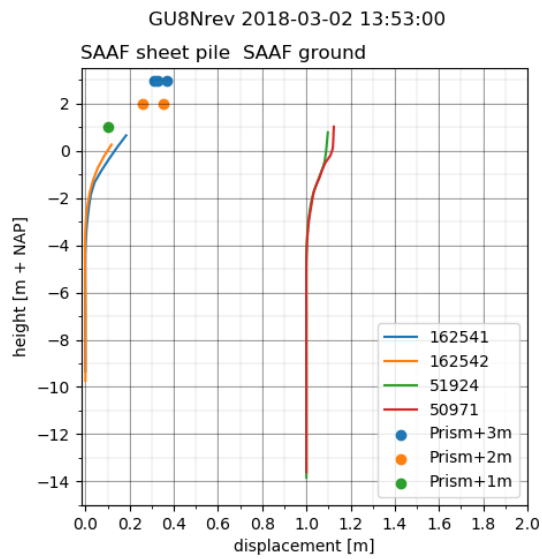

Figure 9. Horizontal displacements over depth of the SAAF and prisms at the GU8N-rev sheet pile.

3.3 AZ13-700 three double-Z

The AZ13-700 three double-Z is a relative wide panel in respect to the GU8N triple-U profiles, see Figure 4. Since the wall is wider and has a higher bending moment capacity than the GU8N triple-U, the maximum pulling force is also higher at 634kN (figure 10). The AZ13-700 three double-Z profile is stiffer than the GU8N profile. This is also reflected in horizontal displacements (figure 11). The fixation level where rotation starts is about -4.0m NAP due to the higher stiffness.

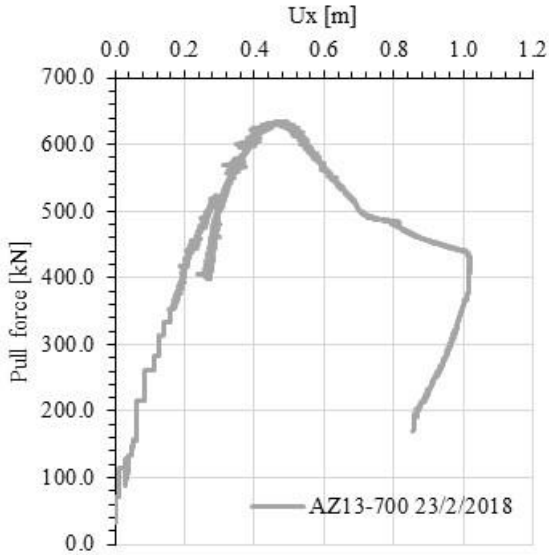

Figure 10. Force-displacement diagram AZ13-700

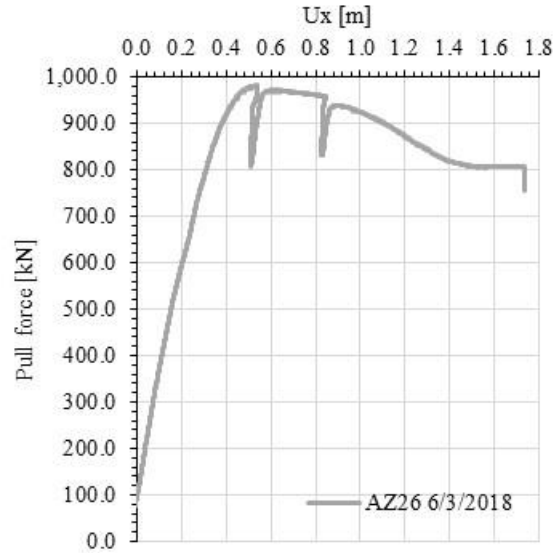

Figure 12. Force-displacement diagram AZ26

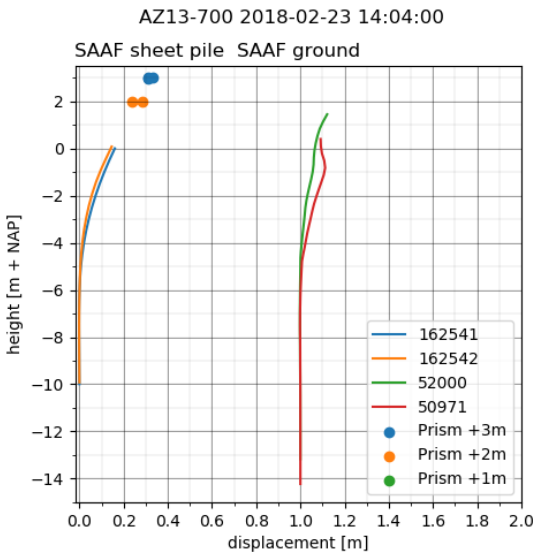

Figure 11. Horizontal displacements over depth of the SAAF and prisms at the AZ13-700 sheet pile

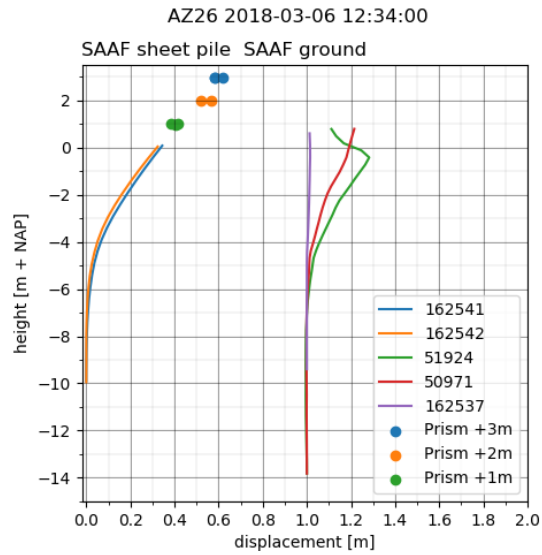

Figure 13. Horizontal displacements over depth of the SAAF and prisms at the AZ26 sheet pile.

3.4 AZ26 three double-Z

The AZ26 three double-Z is the strongest profile that has been tested as part of the pullover test program, a maximum pull-force of 982kN is reached. The fixation level where rotation starts is about -6.0m NAP due to the high stiffness. The results in figure 12 also show that after reaching the maximum pull-force this profile allows for large additional displacements with little reduction of the pulling force relative to the other tested profiles. This setup of three double heavier profiles represents also the typical configuration

often used in projects in the Netherlands with sheet pile reinforcement dikes.

Figure 13 shows the deformations of the AZ26 three double-Z-profile. The larger horizontal displacements relate to the deeper point of rotation, compared to the other profiles. In addition, one SAAF is placed at 5m distance of the sheet pile wall to measure the displacements of the soil on a larger distance.

4 FINDINGS

4.1 Failure behavior

In Table 3 an overview is given of the maximum pull force, the pull force at the end of the test and the corresponding horizontal displacements. For all the profiles it can be observed that if a fully embedded sheet pile fails it still has a certain degree of strength and is still able to mobilize soil and redistribute the soil stresses.

The AZ26 profile has a relatively small reduction of pulling force compared to the other profiles. This corresponds to the classification according to (EN 1993-5, 2007) since this profile is a section class 2 profile in which some degree of plastic rotation capacity is expected.

Table 3. Comparison POT test results

Type	AZ26	AZ13-700	GU8N	GU8N-rev
F_{max}	982	634	180	179
u_{xFmax} [m]	0.53	0.54	0.33	0.32
F_{end}	800 (-18%)	400 (-32%)	140 (-23%)	120 (-31%)
$u_{x;end}$	1.53 (+189%)	1.01 (+87%)	0.95 (+188%)	0.66 (+106%)

4.2 Local buckling behavior

After performing the pullover tests the sheet piles have been excavated to investigate the failure mechanism. Figure 14 shows as example the buckled compression flange of the GU8N-rev triple-U.

Figure 14. Excavated GU8N-rev with local buckling

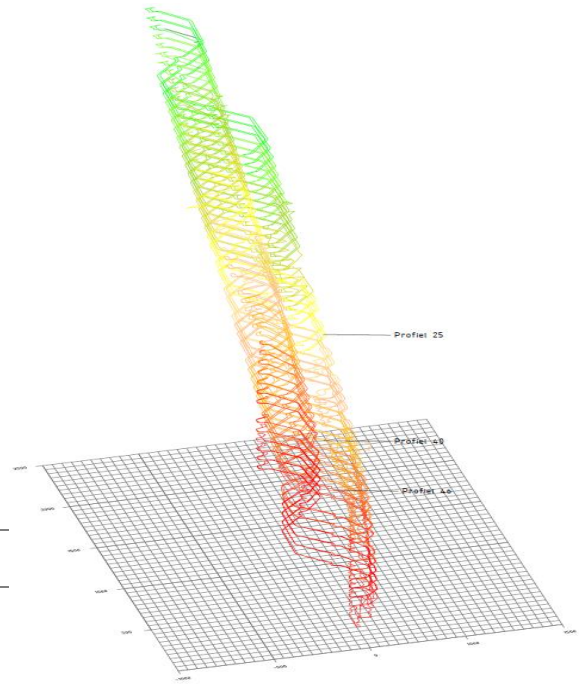

Figure 15. 3D scan of deformed GU8N-rev

In addition to the visual inspection of the excavated sheet piles 3D scans have been made to record the deformed shape of the entire profile, see Figure 15. Based on the 3D-scans it is observed that the buckling and plasticity is limited to approximately 0.5m height. The shape of the rest of the profile did not change significantly.

4.3 Gapping

During the pullover test the sheet piles are pulled forward resulting in a gap at the back of the sheet pile wall. Due to the undrained behavior of the cohesive soil the soil remains almost perfectly vertical and the water level in this gap drops significantly below the original water table effectively reducing the loading on the sheet pile.

Figure 16. Gapping behind sheet pile wall AZ26

5 CONCLUSIONS

Pullover tests have been performed to gain more insight in the soil-structure interaction and the structural behavior of sheet piles beyond maximum bending capacity.

The extensive measurements will provide more information on the maximum bending capacity of Class 2 and 3 profiles. A clear difference between the AZ26 and the other profiles can be observed.

The extensive measurements will provide more information on the effect of discontinues walls (panels).

The results of the POT have been used as input for the test protocol for the FST sheet pile dike. Both the soil parameters and maximum bending capacity of the sheet piles could be better estimated.

The results will be used for the back analyses of the FST sheet pile dike.

6 ACKNOWLEDGEMENTS

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